Understanding the Flow Physics of Shock Boundary Layer Interactions Using CFD and Numerical Analyses

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4/24/13

Outline

- Introduction
- Geometry and Modeling
- Cases
- Results
- Conclusions
- Future Work

Introduction

- SBLI's are not trivial in nature and are very three dimensional flows.
- Physics associated with SBLI's that are often ignored in numerical modeling:
  - Heat transfer boundary conditions
  - Geometry sensitivities
  - Laminar vs. turbulent flow assumptions

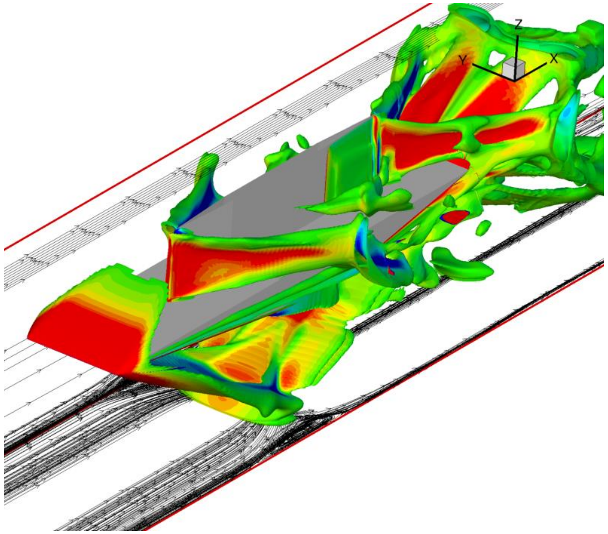


Figure from "Computational Fluid Dynamics Investigation into the Shock Boundary Layer Interactions in the "Glass Inlet" Wind Tunnel" by D. Galbraith, courtesy of M. Galbraith

Introduction

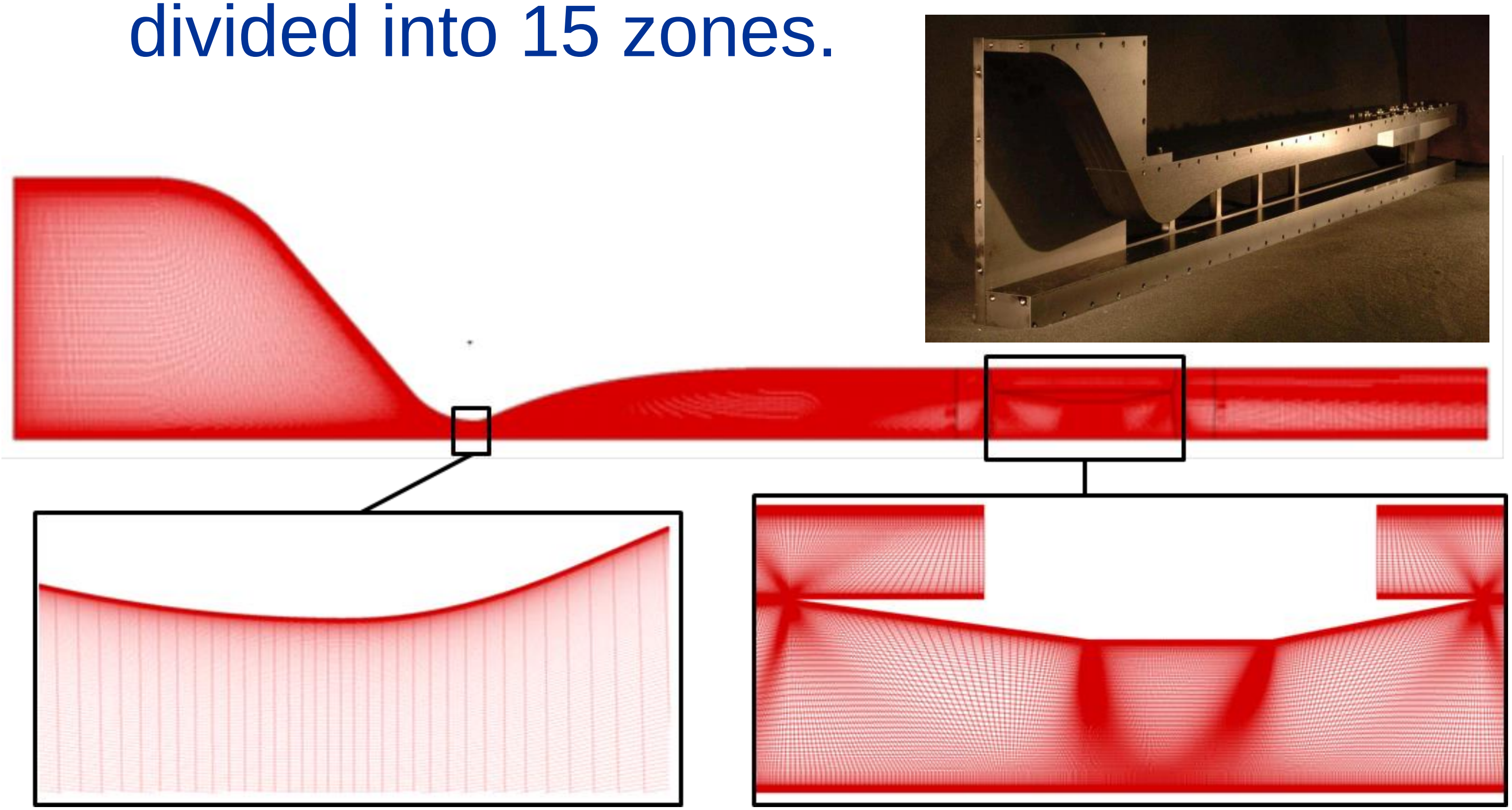
- Workshop held at the 48th AIAA Aerospace Sciences Meeting.
  – CFD analyses failed to match experimental data.
- Further CFD analyses performed at the University of Cincinnati/NASA Glenn Research Center.
  – University of Michigan Glass Tunnel
    - Mach 2.75 freestream
    - 7.75 degree semi-spanning wedge

Introduction

- Focus on the *u* and *v* velocity components.
  - Felt that the CFD and post-processing calculations from the workshop missed the peak *u* velocity as well as the location of the shock as defined by the *v* velocity profile.
- Explored alternatives to the previous workshop error metric.

Geometry and Modeling

- 3D overset grid* with 56 million grid points divided into 15 zones.



*Grid based on the one made by Marshall Galbraith

Solver

- OVERFLOW Version 2.2E
- Ran on 20 Quad-Core Xeon X5570 (NASA Pleiades-Nehalem).
- Local time-step scaling.
  - CFLMIN=5
  - CFLMAX=20
- Cases took about 68hrs to converge.

CFD Cases

- Standard
- Isothermal
- Modified Geometry
- Trip
- Combined
- TKE
- MUT
- Particle Lag*
- Total Temperature**
- Perfect vs. Non-Ideal**

*Post-processing only
**Quasi-1D only

Standard Case

- Geometry: As designed (A/A*=3.7062)
- SST turbulence model
  - Modified SST (SST-GY)
  - BSL
- All surfaces adiabatic
- $TKE_{INF}=3.576 \times 10^{-1}\ m^2/s^2$
- $Re_{T,INF}=0.3$
- Constant $c_p/c_v=1.4$

Isothermal Case

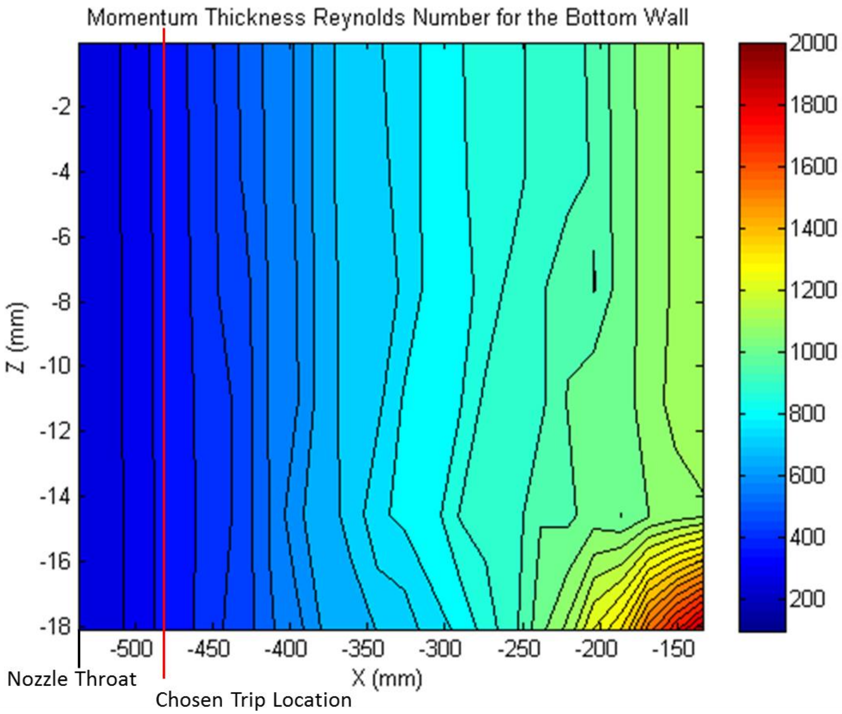
- Geometry: As designed (A/A*=3.7062)
- SST turbulence model
- Top and bottom walls and wedge isothermal (295.7 K), all other surfaces (including bottom window) adiabatic.
- $TKE_{INF}=3.576\times10^{-1}\ m^2/s^2$
- $Re_{T,INF}=0.3$
- Constant $c_p/c_v=1.4$

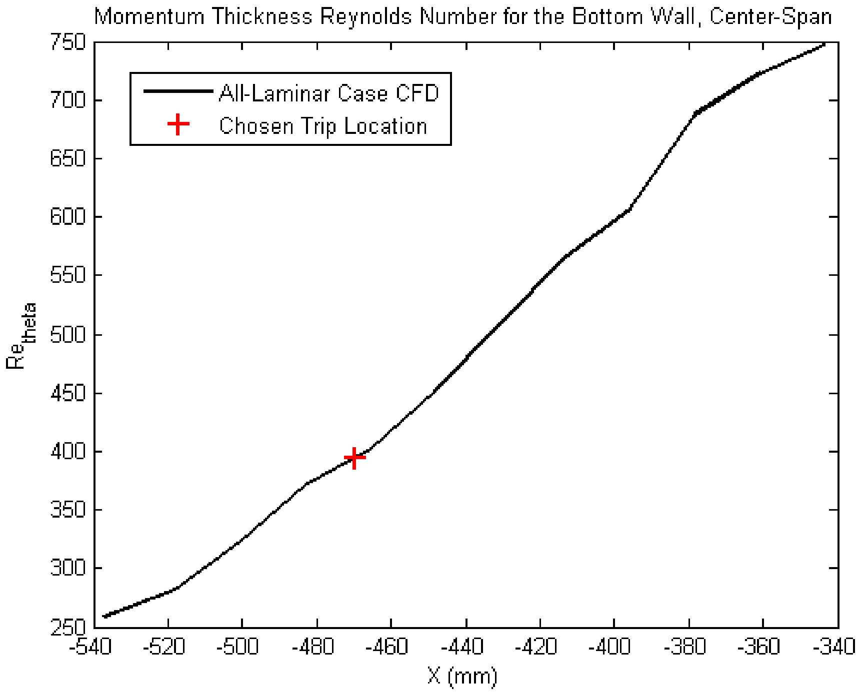
Modified Geometry Case

- Geometry: As currently installed with max tolerance (A/A*=3.7847)
- SST turbulence model
- All surfaces adiabatic
- $TKE_{INF}=3.576x10^{-1}$ m^2/s^2
- $Re_{T,INF}=0.3$
- Constant $c_p/c_v=1.4$

Trip Case

- Geometry: As designed ($A/A^*=3.7062$)
- Laminar from inlet to 67.6mm downstream of the throat, SST turbulence model for remaining regions.
  - Trip at approximately where $Re_\theta=400$, based on all-laminar case (see next slide)
- All surfaces adiabatic
- $TKE_{INF}=3.576\text{x}10^{-1}\ m^2/s^2$
- $Re_{T,INF}=0.3$
- Constant $c_p/c_v=1.4$


Momentum Thickness Reynolds Number for the Bottom Wall
Z (mm)
X (mm)
Nozzle Throat
Chosen Trip Location
2000
1800
1600
1400
1200
1000
800
600
400
200


Momentum Thickness Reynolds Number for the Bottom Wall, Center-Span
All-Laminar Case CFD
Chosen Trip Location
Re_{theta}
X (mm)

Combined Case

- Geometry: As currently installed with max error (A/A*=3.7847)
- Laminar from inlet to 67.6mm downstream of the throat, SST turbulence model for remaining regions.
  - Ran with SST-GY and BSL in addition to SST.
- Top and bottom walls and wedge isothermal (295.7 K), all other surfaces (including bottom window) adiabatic.
- $TKE_{INF}=3.576 \times 10^{-1}\ m^2/s^2$
- $Re_{T,INF}=0.3$
- Constant $c_p/c_v=1.4$

TKE Case

- Geometry: As designed (A/A*=3.7062)
- SST turbulence model
- All surfaces adiabatic
- $TKE_{INF}=3.576x10^{3}$ m^{2}/s^{2}
- $Re_{T,INF}=0.3$
- Constant $c_p/c_v=1.4$

MUT Case

- Geometry: As designed (A/A*=3.7062)
- SST turbulence model
- All surfaces adiabatic
- $TKE_{INF}=3.576x10^3\ m^2/s^2$
- $Re_{T,INF}=3.0$
- Constant $c_p/c_v=1.4$

Particle Lag Simulation

- Time constants represent 50%, 75%, and 100% total particle relaxation time:
  - Short Lag (1.8 µs)
  - Medium Lag (3.7 µs)
  - Long Lag (5.5 µs)

$$x' = x + u_x \tau$$

$$y' = y + v_y \tau$$

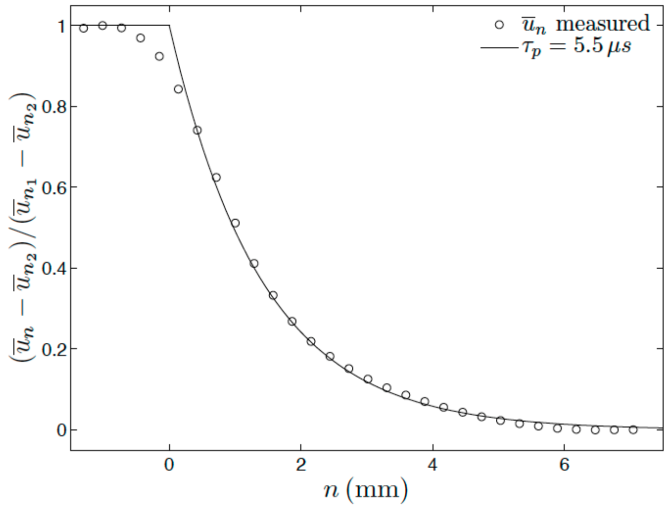


Figure 3.1: Measured particle response through an oblique shock. The velocity component normal to the shock, $\overline{u}_n$, is normalized by the pre-shock ($\overline{u}_{n_1}$) and post-shock ($\overline{u}_{n_2}$) velocities and shown as a function of the shock-normal direction, n. An exponential fit to the data reveals the particle relaxation time, $\tau_p = 5.5\,\mu$s.

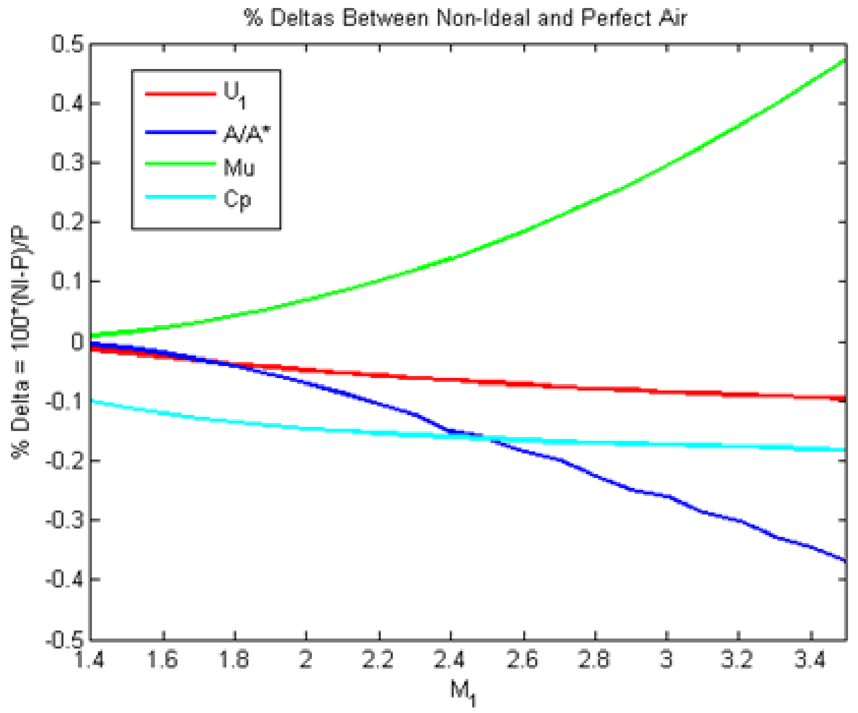
Figure from “Experimental Study of Passive Ramps for Control of Shock-Boundary Layer Interactions” by A. Lapsa

Total Temperature Sensitivity

- Discrepancy in total temperature:
  - Workshop: 293 K
  - Experiment: 295.7 ±1 K
- Using 1D perfect gas equations:
  - 2.8 m/s (0.47% of a 600 m/s freestream velocity).
  - ±1 K alone is ± 1 m/s (0.17% of a 600 m/s freestream velocity).

Perfect vs. Non-Ideal Air

- MATLAB code developed to perform quasi-1D flow calculations for perfect and non-ideal air.
- Very little difference between perfect and non-ideal air calculations



Flat Plate Study

- 2D Zero Pressure Gradient case from Turbulence Model Benchmarking Working Group.
- Ran with SST, SST-GY, BSL, and K-Omega

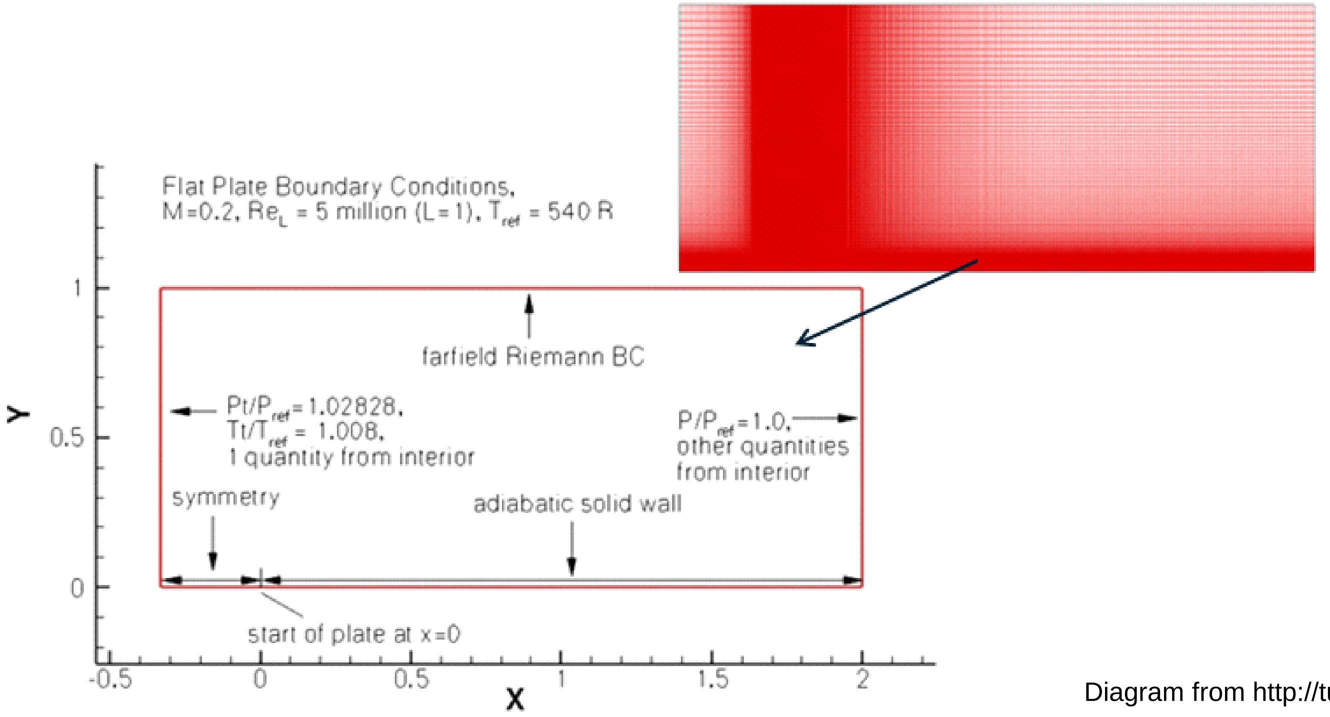
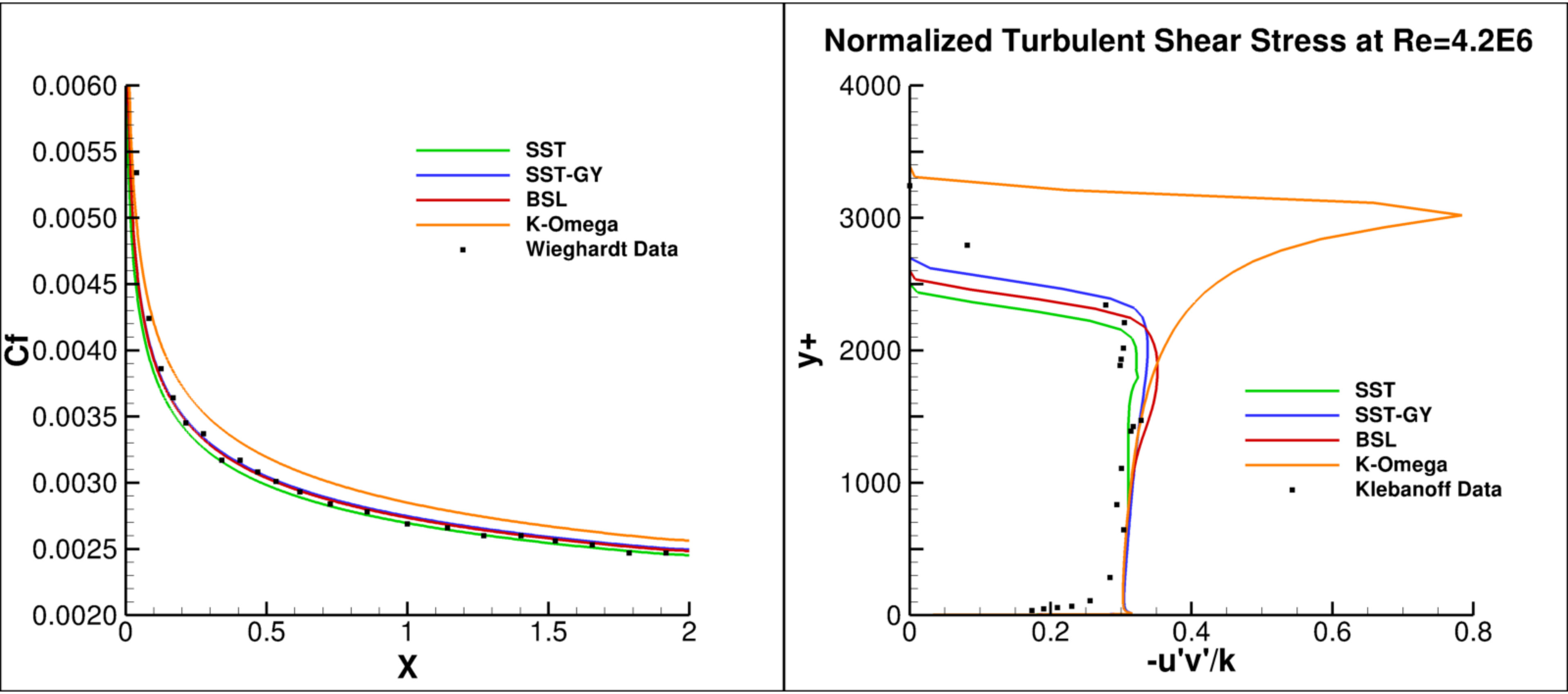
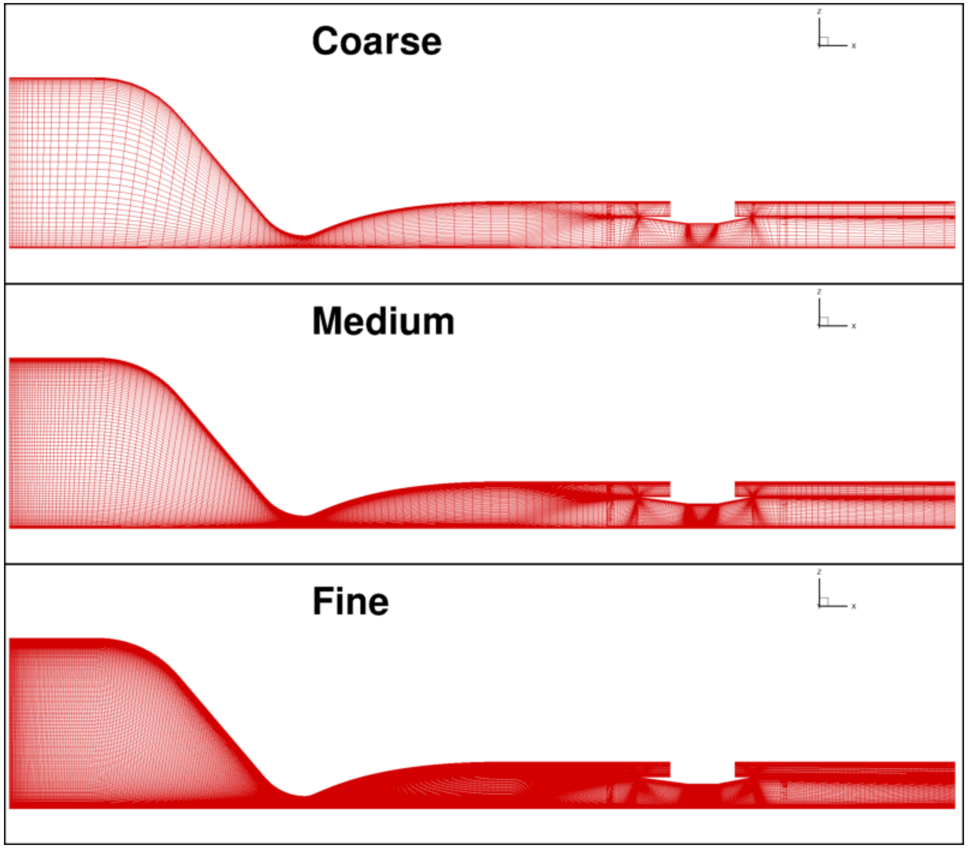


Diagram from http://turbmodels.larc.nasa.gov/FlatPlate/



Solutions agree well with each other (except K-Omega)

Grid Resolution Study



Inlet: Tt=295.7 K, Pt=98000 Pa

Throat

	Coarse	Medium	Fine
Tt (K)	296.530	295.909	295.701
Pt (Pa)	98761.8	98199.4	98009.4
M	0.95217	0.94737	0.94703

Upstream

	Coarse	Medium	Fine
Tt (K)	296.504	295.960	295.704
Pt (Pa)	98134.4	98103.0	97996.9
M	2.73365	2.73637	2.74482

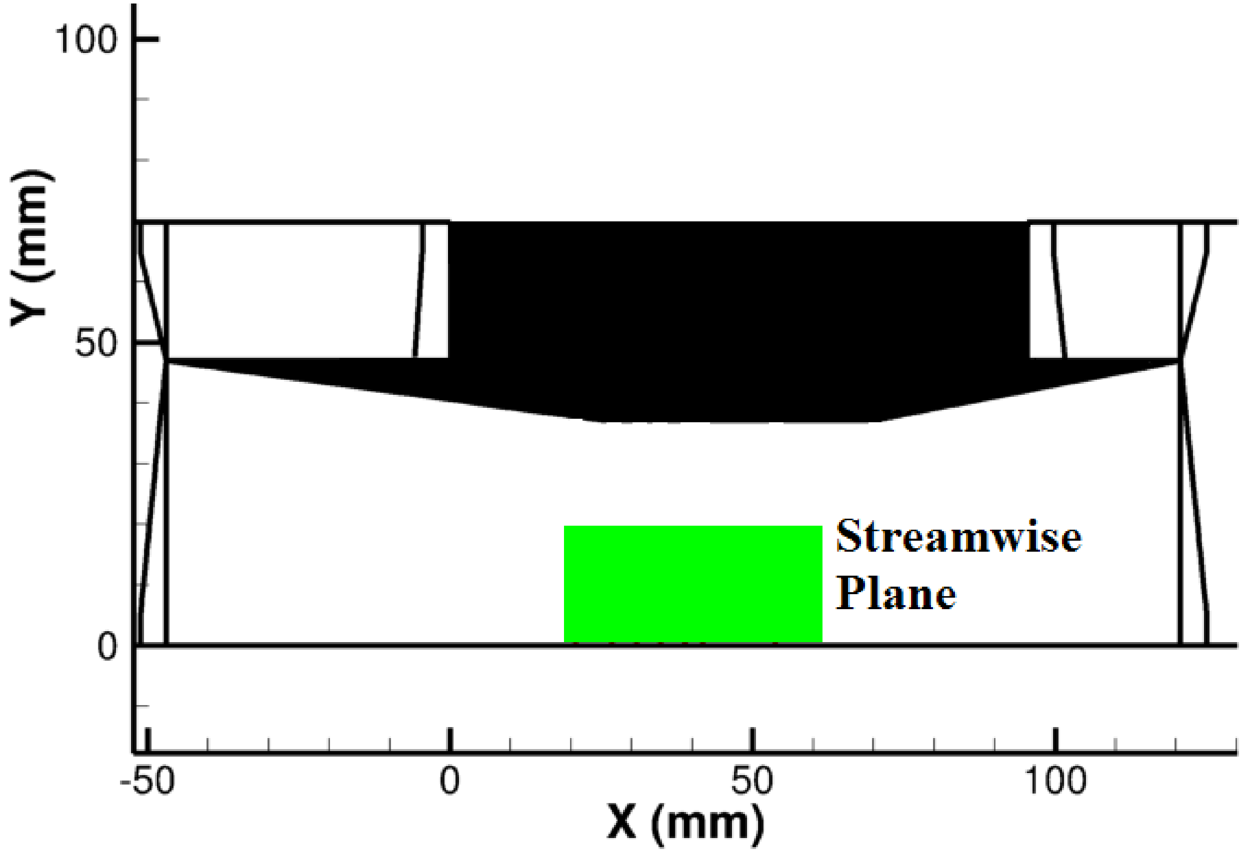
Downstream

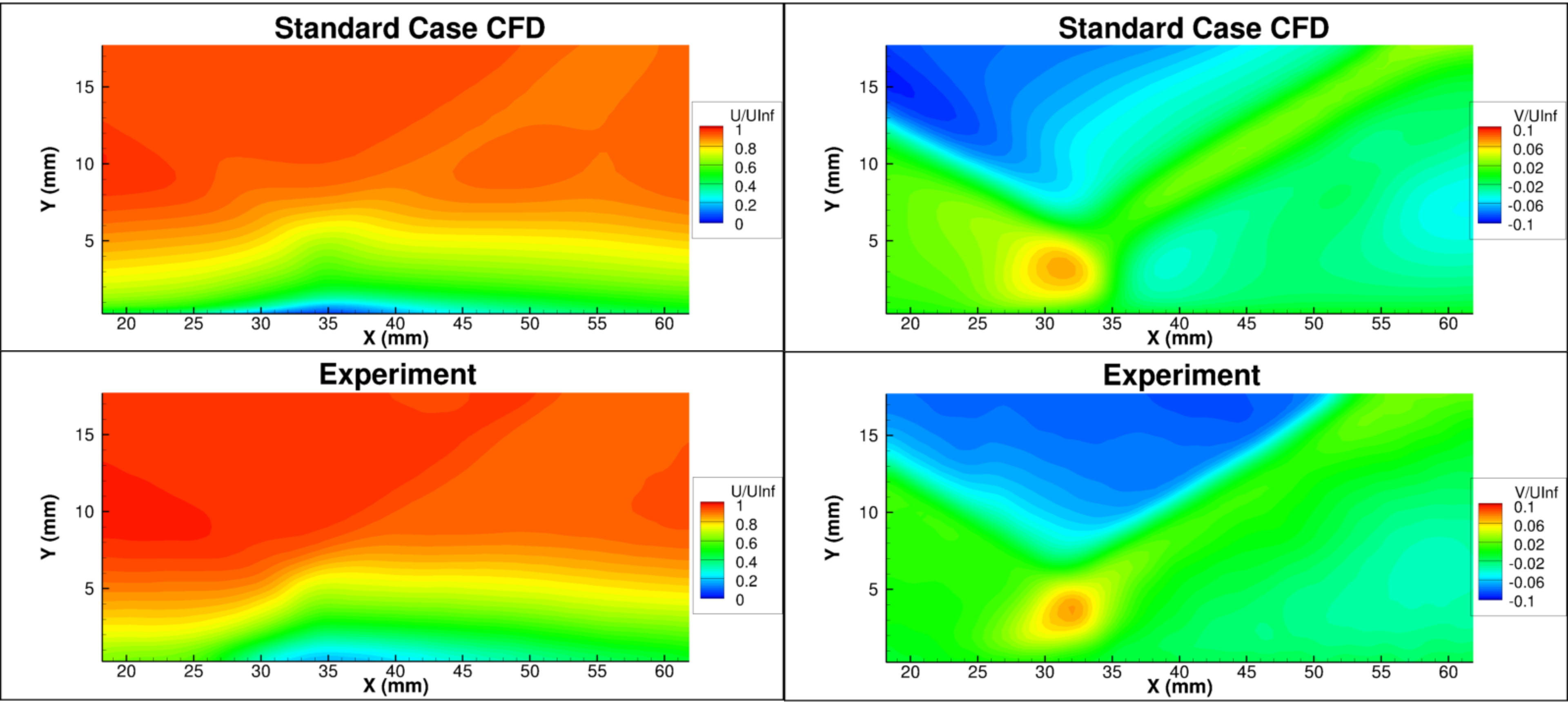
	Coarse	Medium	Fine
Tt (K)	296.173	296.073	295.742
Pt (Pa)	96083.7	96459.3	96247.1
M	2.49111	2.48308	2.47317

Mass flow conserved within < 0.5%

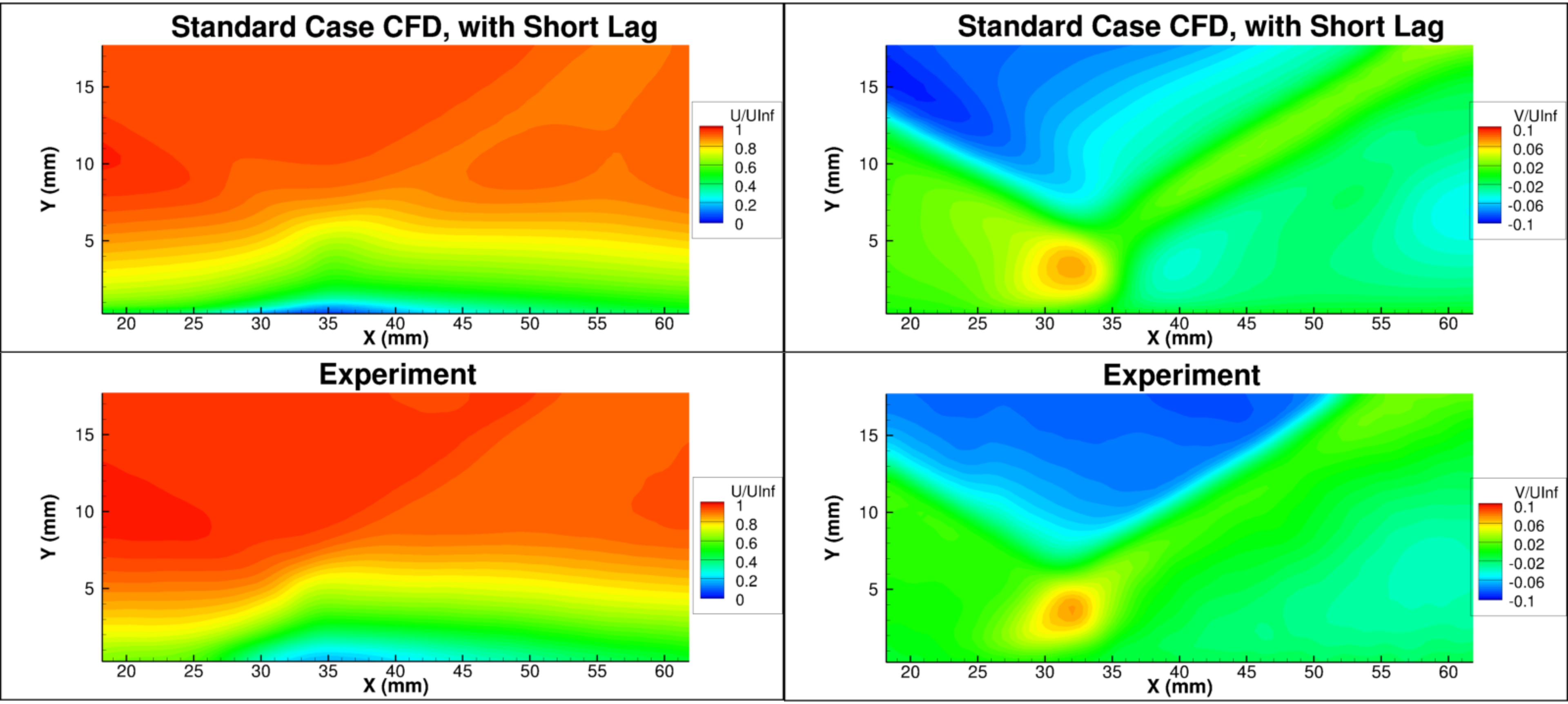
Results

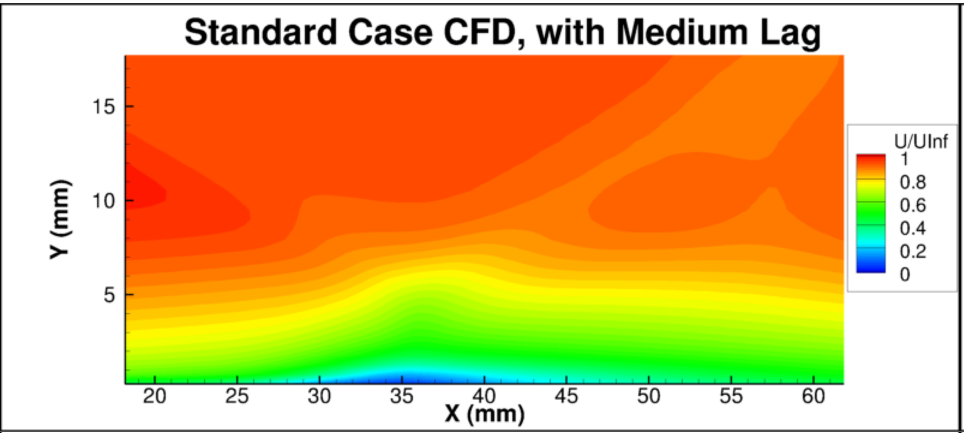
Data Comparison Plane

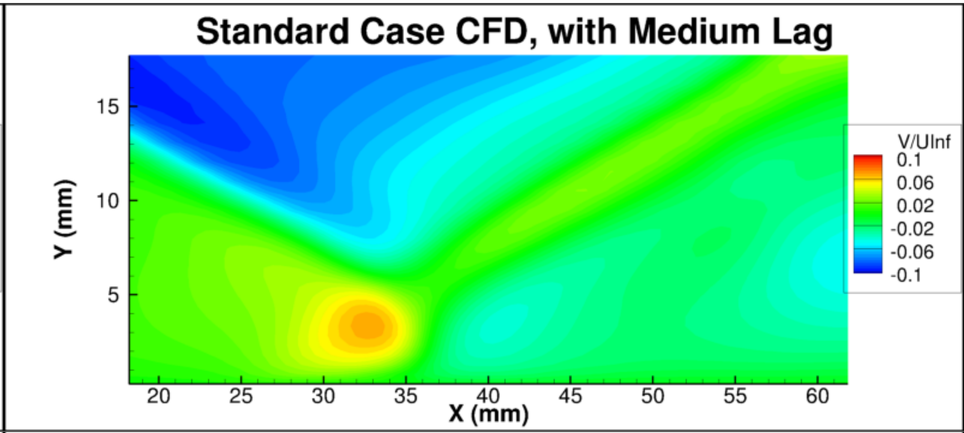


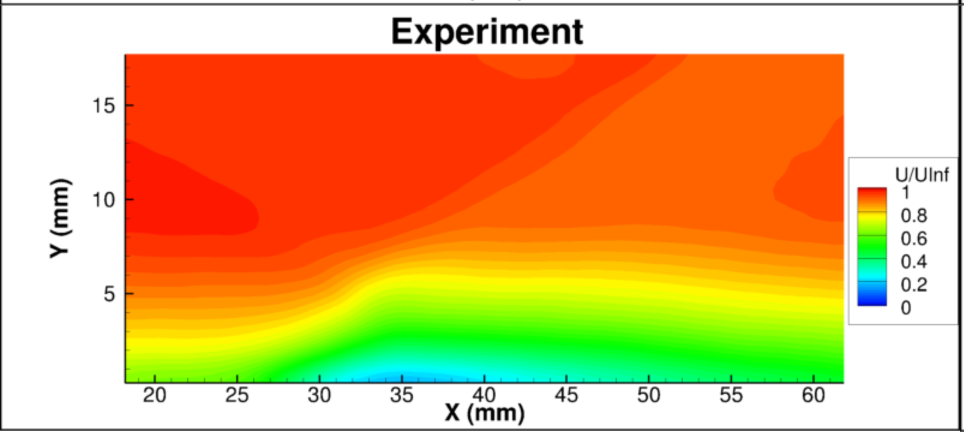


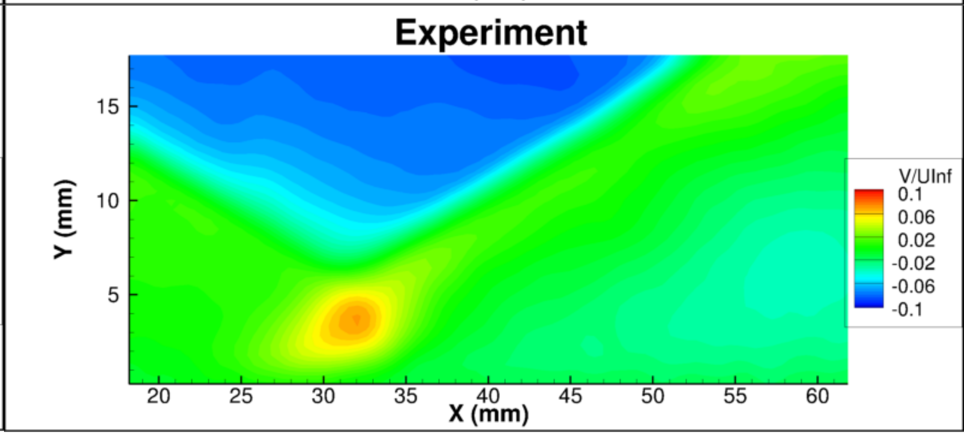
Standard Case CFD
U/UInf
1
0.8
0.6
0.4
0.2
0
Y (mm)
X (mm)
Standard Case CFD
V/UInf
0.1
0.06
0.02
-0.02
-0.06
-0.1
Experiment
U/UInf
Experiment
V/UInf

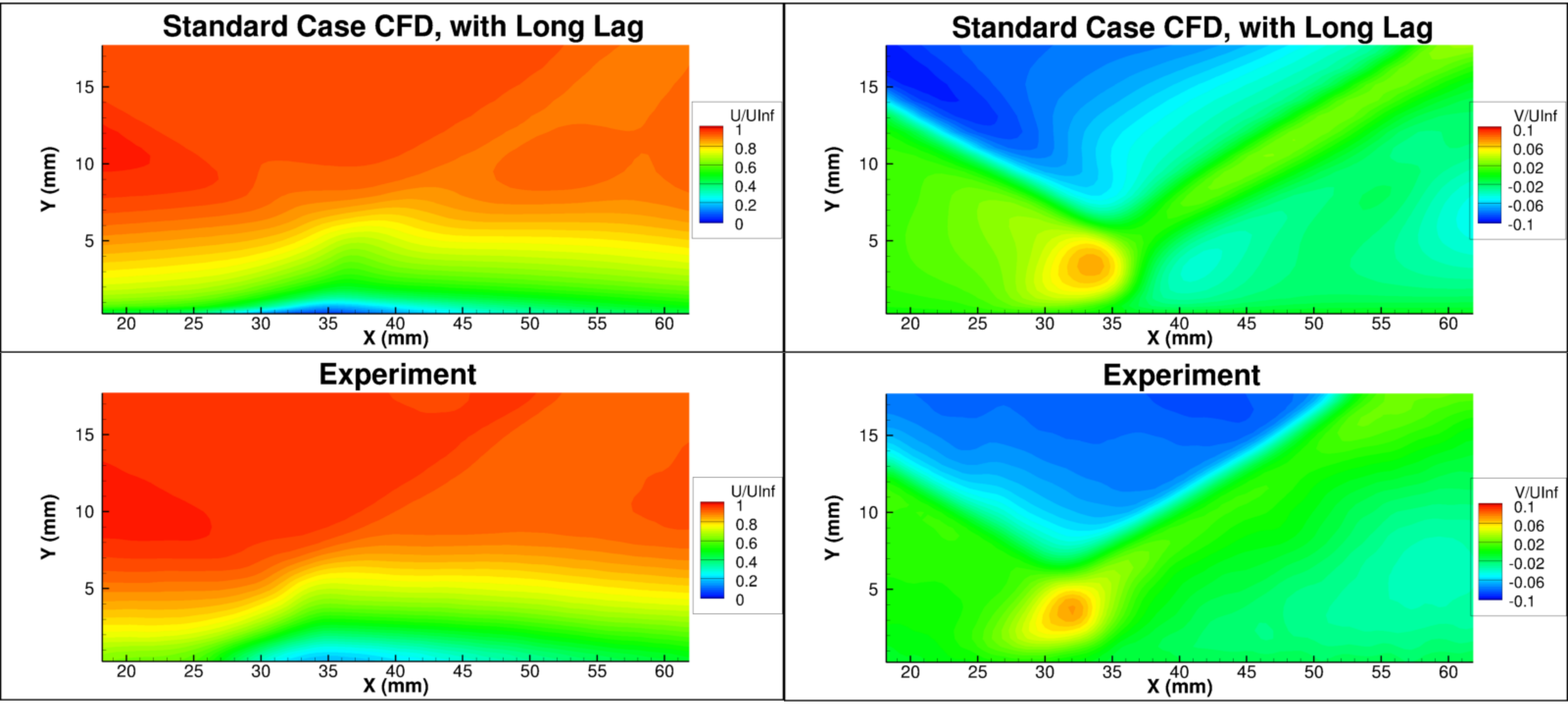

Standard Case CFD, with Short Lag
Y (mm)
X (mm)
U/UInf
1
0.8
0.6
0.4
0.2
0
Standard Case CFD, with Short Lag
V/UInf
0.1
0.06
0.02
-0.02
-0.06
-0.1
Experiment
Experiment

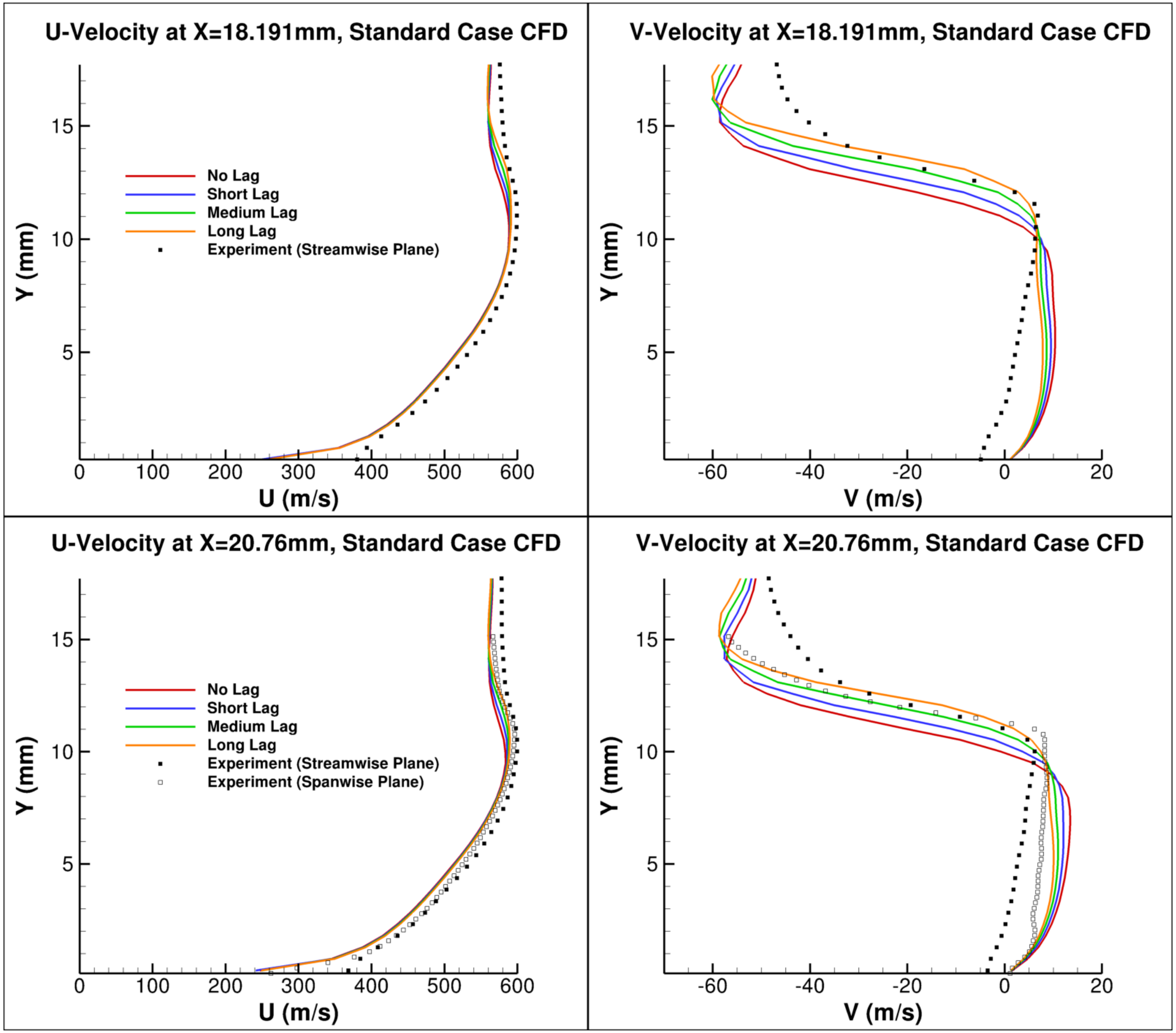

Standard Case CFD, with Medium Lag
Y (mm)
15
10
5
X (mm)
20 25 30 35 40 45 50 55 60
U/UInf
1
0.8
0.6
0.4
0.2
0


Standard Case CFD, with Medium Lag
Y (mm)
15
10
5
X (mm)
20 25 30 35 40 45 50 55 60
V/UInf
0.1
0.06
0.02
-0.02
-0.06
-0.1

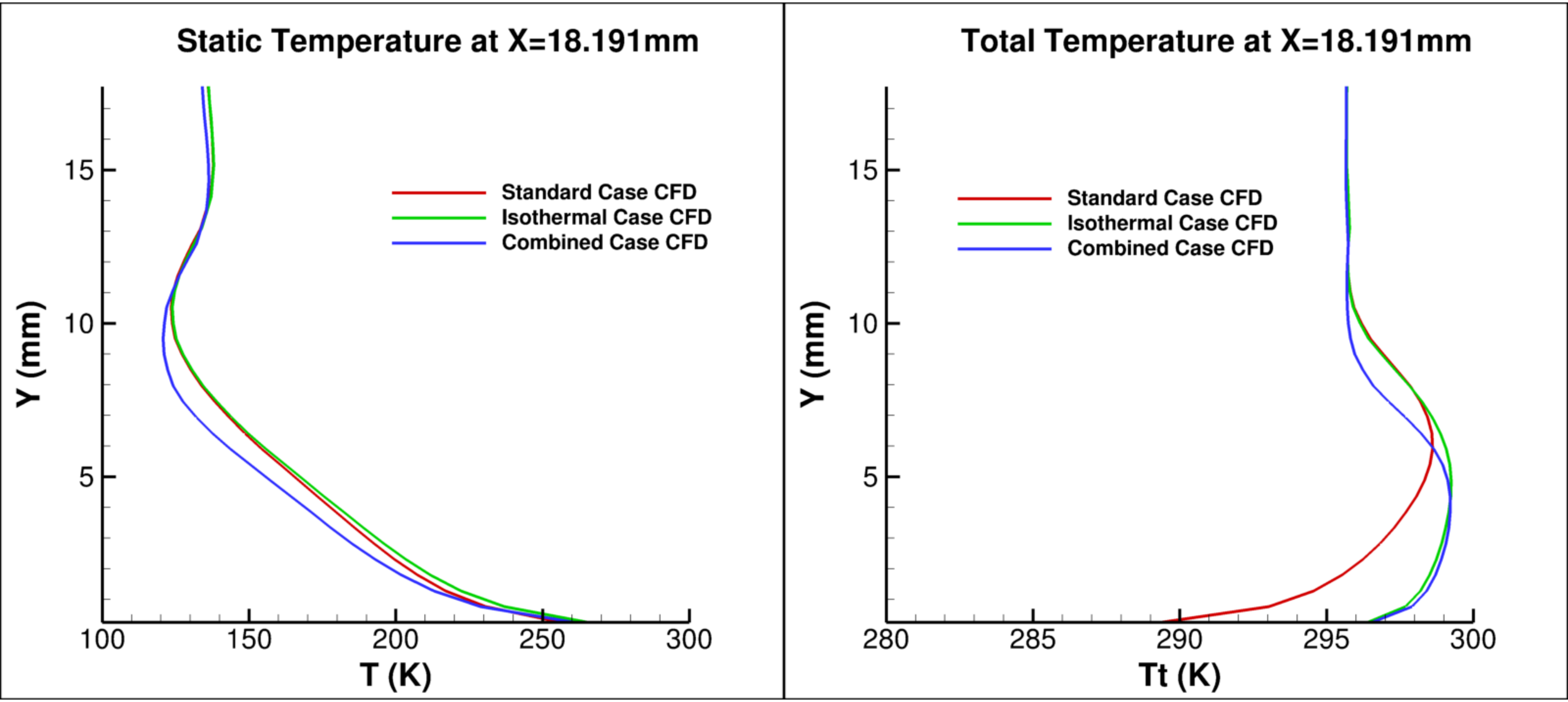

Experiment
Y (mm)
15
10
5
X (mm)
20 25 30 35 40 45 50 55 60
U/UInf
1
0.8
0.6
0.4
0.2
0


Experiment
Y (mm)
15
10
5
X (mm)
20 25 30 35 40 45 50 55 60
V/UInf
0.1
0.06
0.02
-0.02
-0.06
-0.1

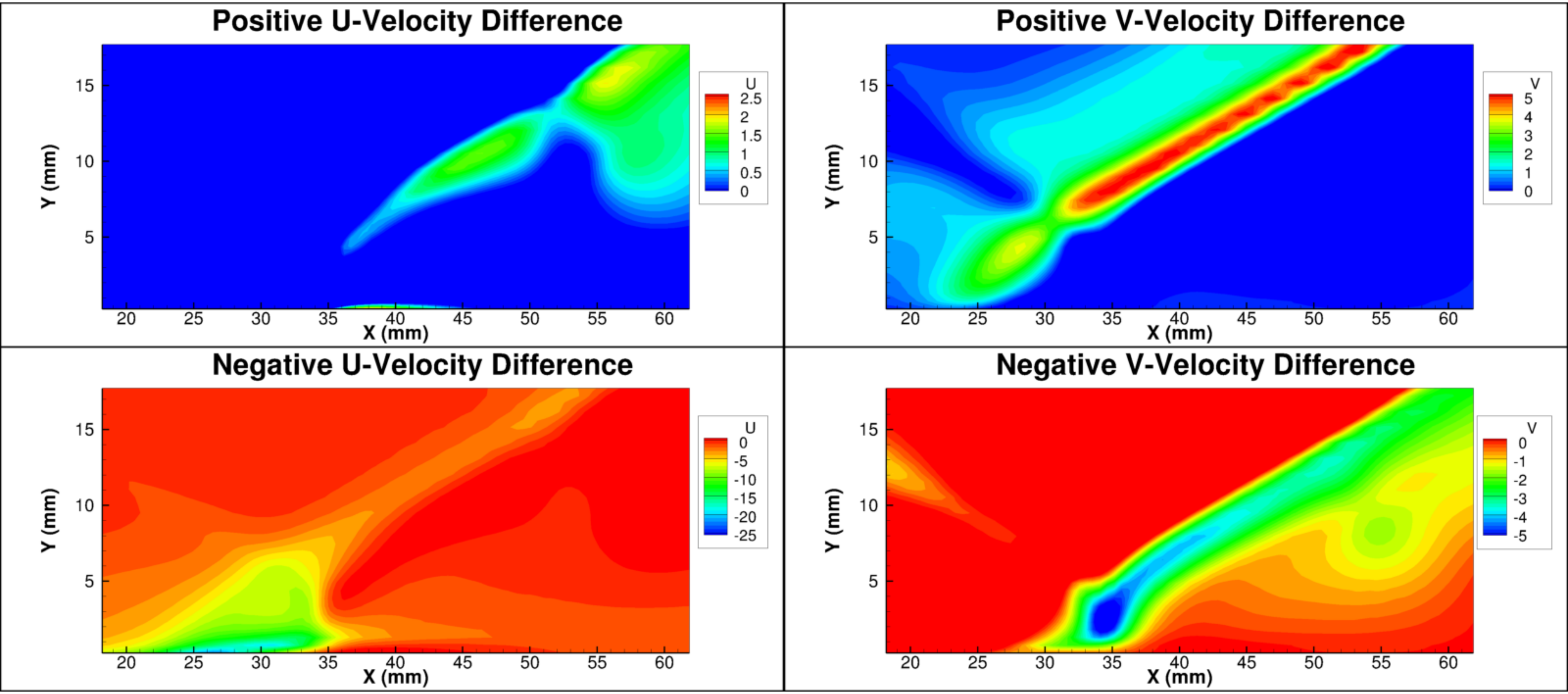

Standard Case CFD, with Long Lag
Y (mm)
X (mm)
U/UInf
1
0.8
0.6
0.4
0.2
0
Standard Case CFD, with Long Lag
V/UInf
0.1
0.06
0.02
-0.02
-0.06
-0.1
Experiment
Experiment


U-Velocity at X=18.191mm, Standard Case CFD
V-Velocity at X=18.191mm, Standard Case CFD
U-Velocity at X=20.76mm, Standard Case CFD
V-Velocity at X=20.76mm, Standard Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
U (m/s)
V (m/s)
0
100
200
300
400
500
600
-60
-40
-20
20
5
10
15

Isothermal Case



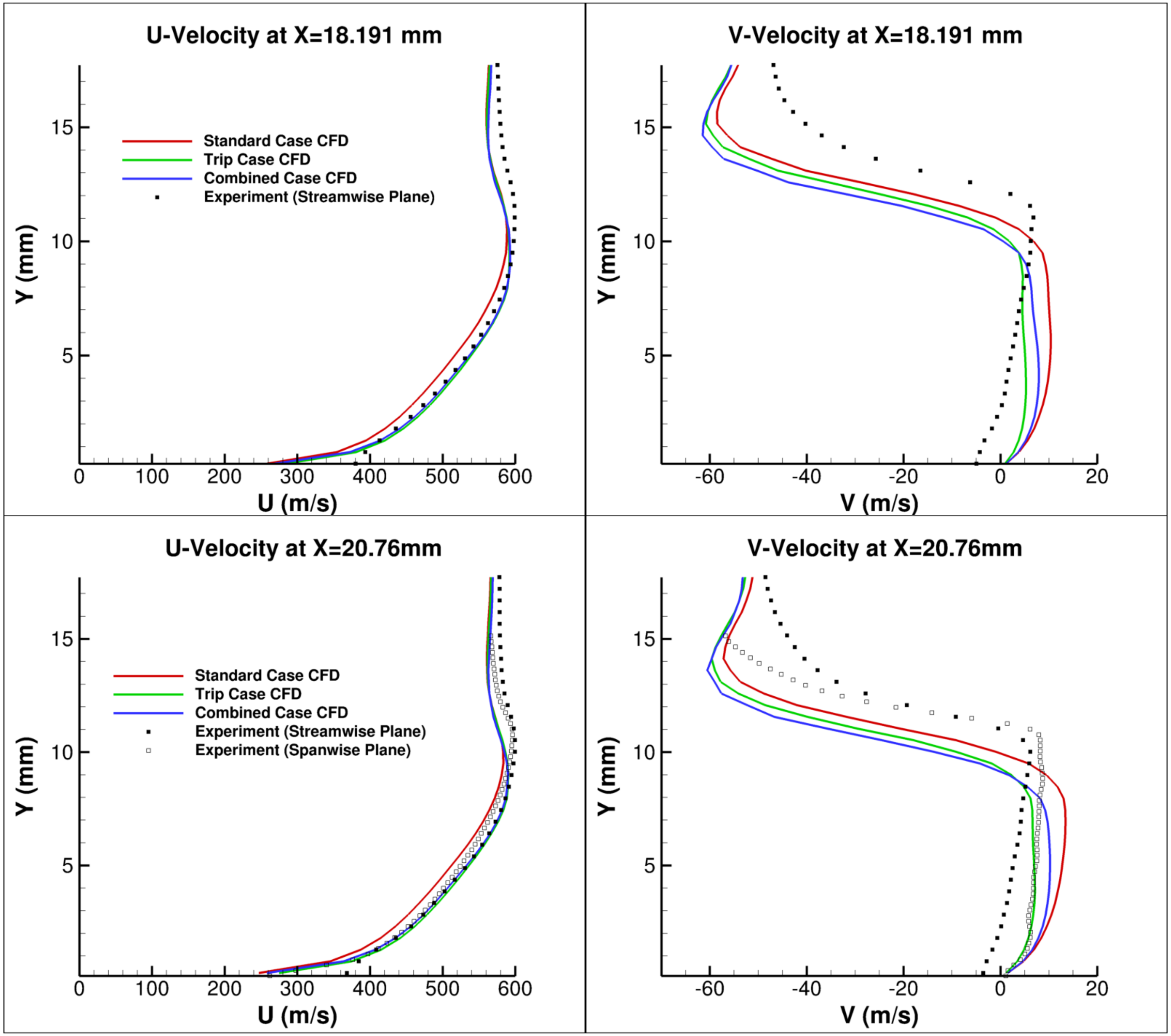
$$\frac{T_{aw}}{T_\infty} = 1 + \frac{r_c}{2}(\gamma - 1)M_\infty^2 \qquad r_c = 92.3\%$$

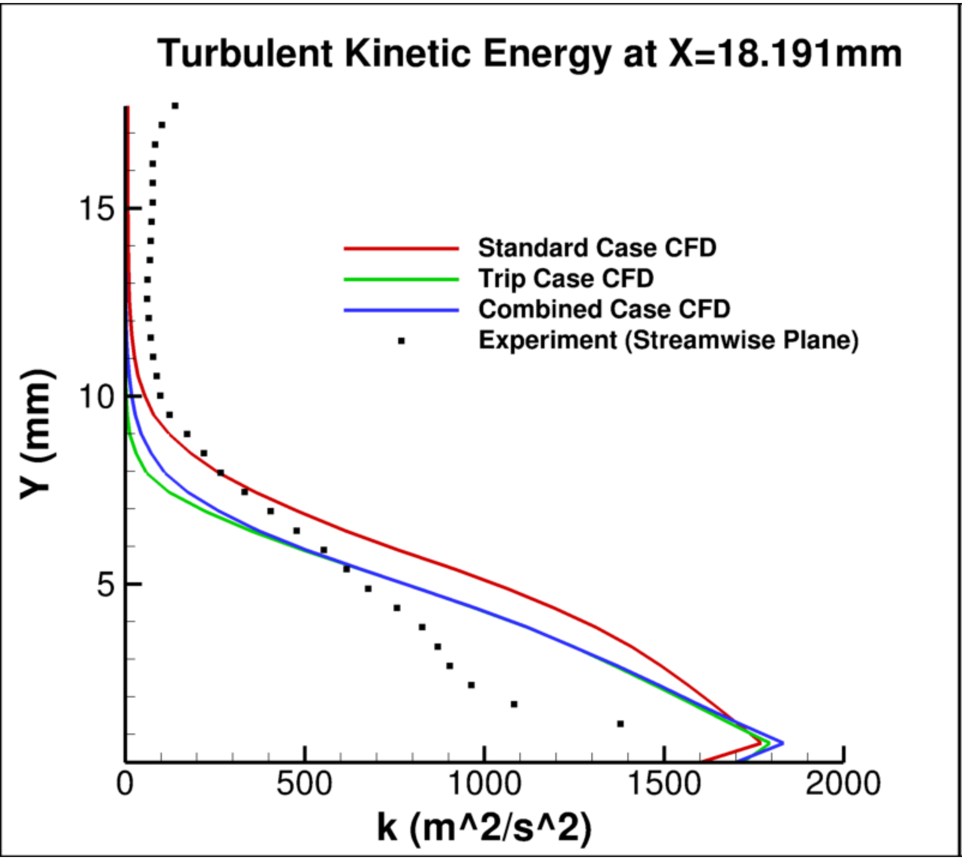


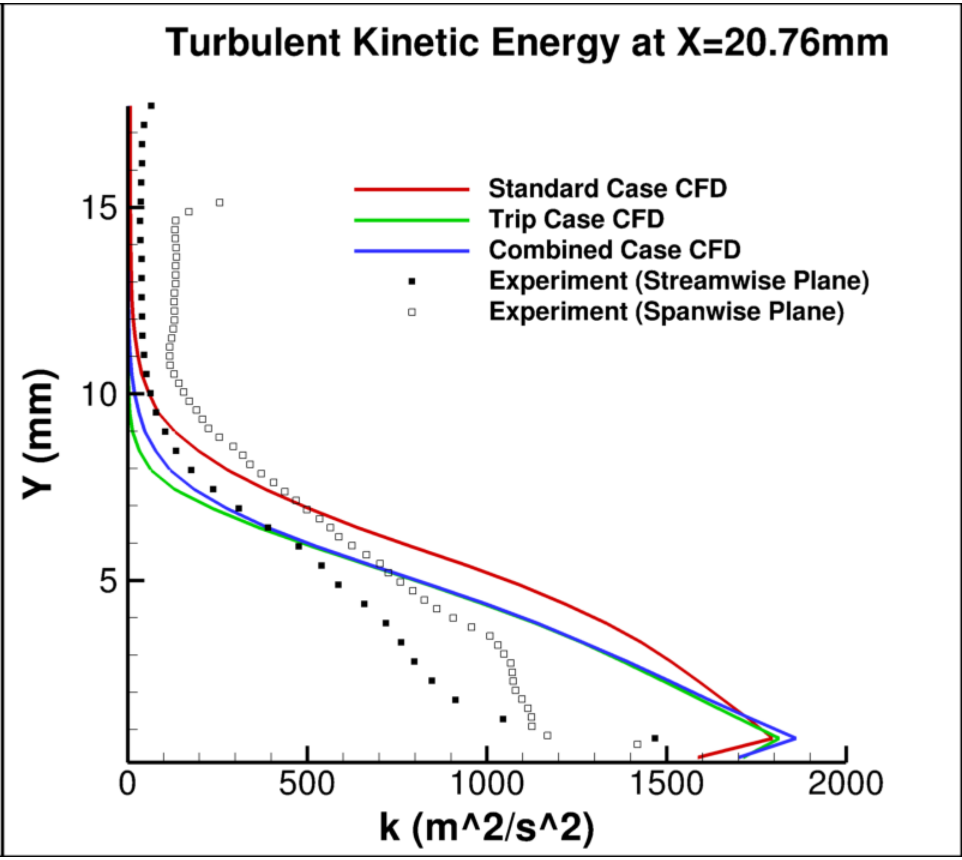
Isothermal case shifts interaction region slightly upstream

Difference=Isothermal-Standard

Trip Case

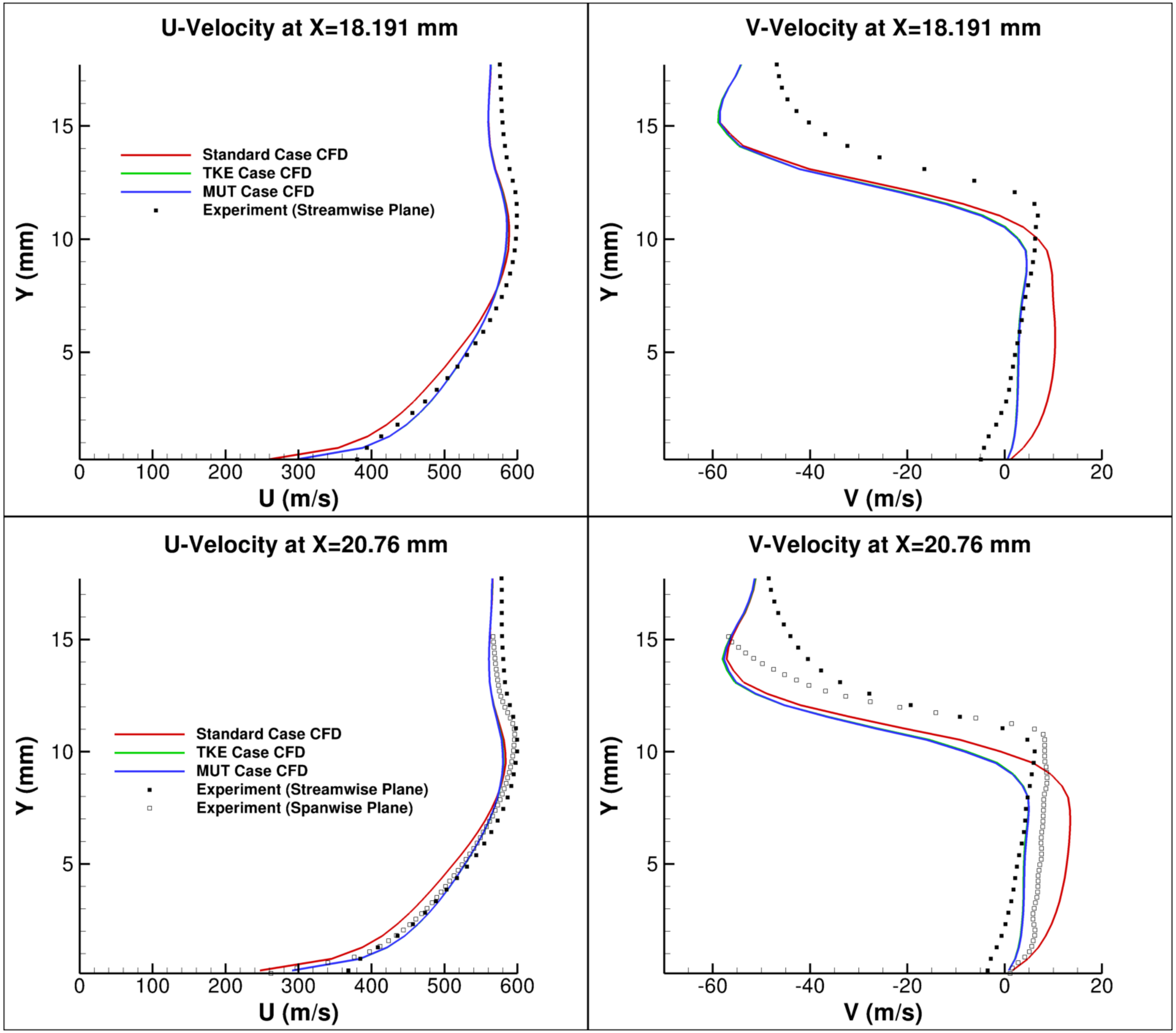

U-Velocity at X=18.191 mm
V-Velocity at X=18.191 mm
U-Velocity at X=20.76mm
V-Velocity at X=20.76mm
Standard Case CFD
Trip Case CFD
Combined Case CFD
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
U (m/s)
V (m/s)
0
5
10
15
100
200
300
400
500
600
-60
-40
-20
20

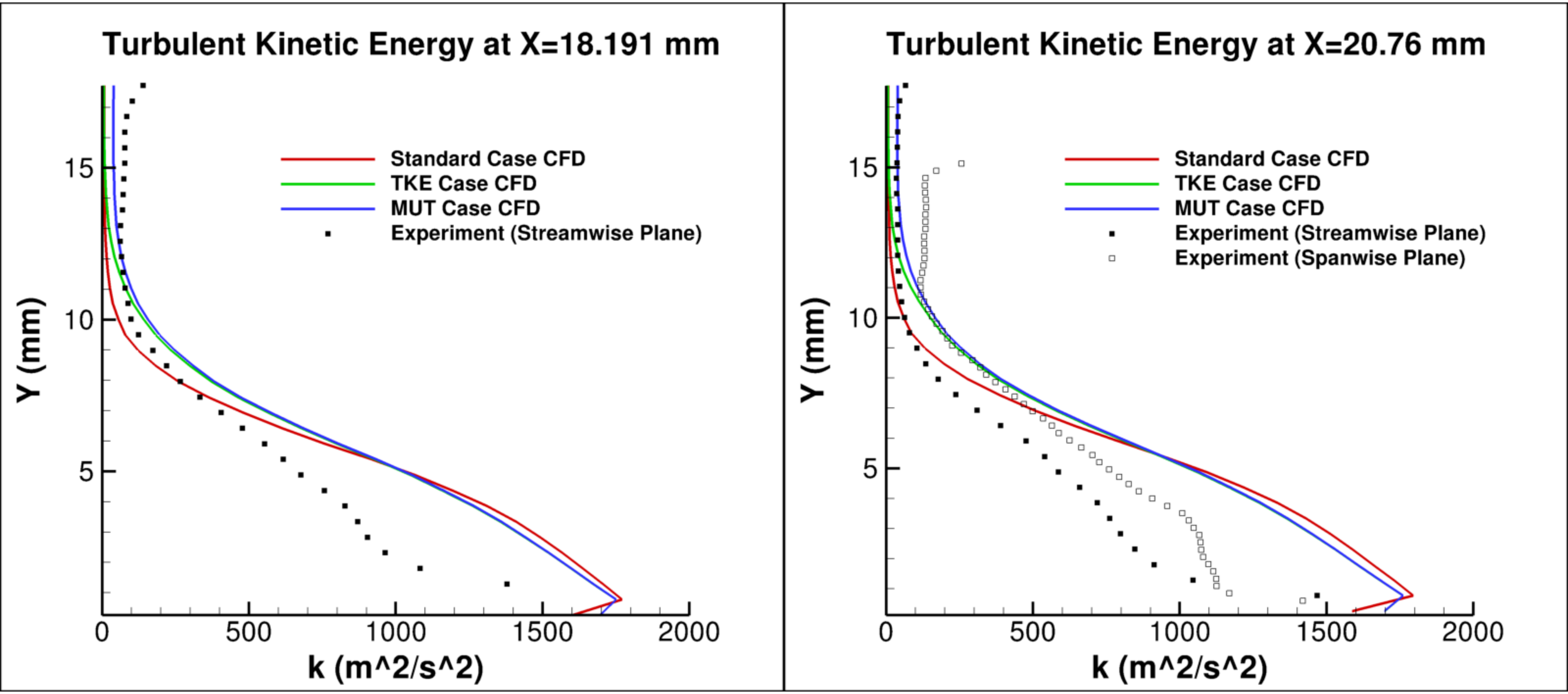




CFD turbulent kinetic energy lower in the freestream

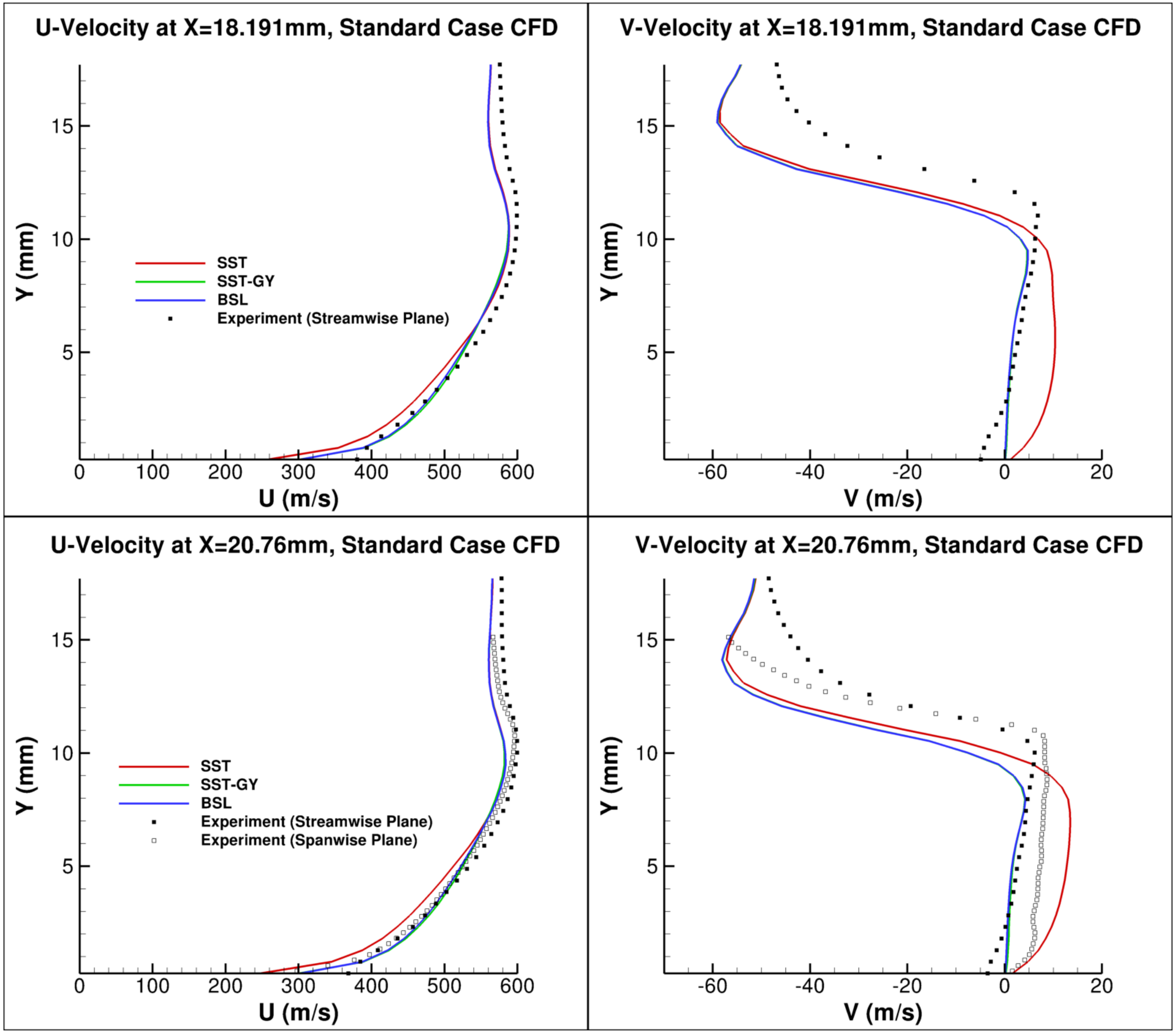
TKE and MUT Cases

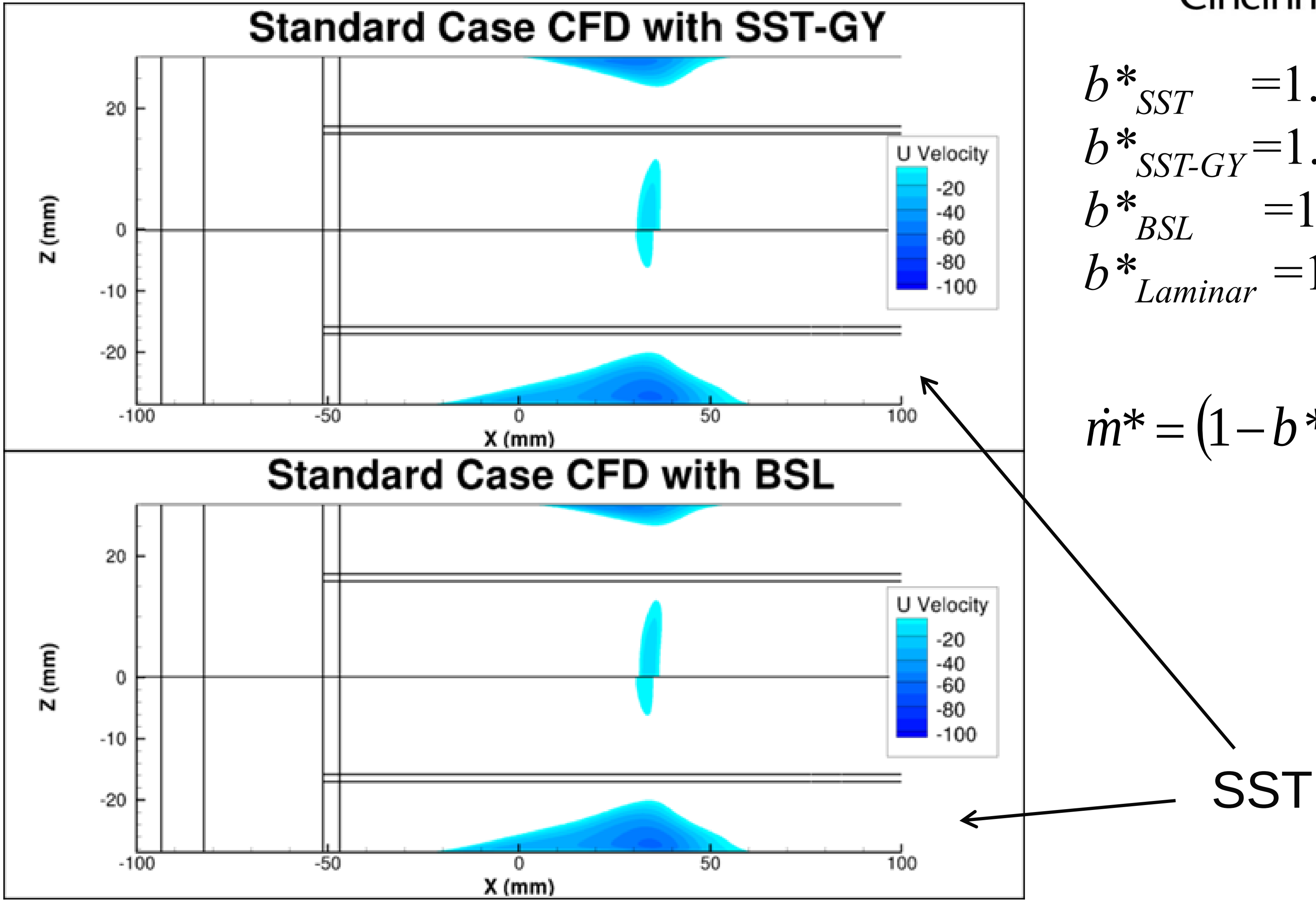

U-Velocity at X=18.191 mm
Standard Case CFD
TKE Case CFD
MUT Case CFD
Experiment (Streamwise Plane)
Y (mm)
U (m/s)
V-Velocity at X=18.191 mm
V (m/s)
U-Velocity at X=20.76 mm
Experiment (Spanwise Plane)
V-Velocity at X=20.76 mm



Increase in freestream TKE results in better agreement with freestream experimental data

Turbulence Model Effects


U-Velocity at X=18.191mm, Standard Case CFD
V-Velocity at X=18.191mm, Standard Case CFD
U-Velocity at X=20.76mm, Standard Case CFD
V-Velocity at X=20.76mm, Standard Case CFD
SST
SST-GY
BSL
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
U (m/s)
V (m/s)
0
100
200
300
400
500
600
-60
-40
-20
20
5
10
15



$$b^*_{SST} = 1.53\%$$
$$b^*_{SST\text{-}GY} = 1.51\%$$
$$b^*_{BSL} = 1.49\%$$
$$b^*_{Laminar} = 1.11\%$$

$$\dot{m}^* = (1 - b^*)\dot{m}^*_{ideal}$$

U<0

Metrics

Error Metric

U Error		V Error	
0.02373	Q	0.008947	Expt.
0.02633	B	0.01158	Standard (Medium Lag)
0.02669	P	0.01185	Standard (Long Lag)
0.02676	Standard (Long Lag)	0.01224	Standard (Short Lag)
0.02747	Standard (Medium Lag)	0.01308	MUT
0.02759	G	0.01331	TKE
0.02840	F	0.01348	Combined (Medium Lag)
0.02853	Standard (Short Lag)	0.01360	Combined (Short Lag)
0.02899	M	0.01375	Combined (Long Lag)
0.02957	I	0.01377	Standard
0.02964	Standard	0.01403	Combined
0.02999	K	0.01414	Trip
0.03020	Standard (SST-GY)	0.01449	B
0.03025	Combined (Short Lag)	0.01514	Isothermal
0.03035	N	0.01621	Modified Geometry
0.03036	Combined (Medium Lag)	0.01682	P
0.03043	TKE	0.01716	G
0.03043	MUT	0.01729	F
0.03047	Combined	0.01771	M
0.03064	Combined (Long Lag)	0.01828	Q
0.03090	Isothermal	0.01867	K
0.03114	Modified Geometry	0.01917	N
0.03115	Standard (BSL)	0.01950	Standard (SST-GY)
0.03129	O	0.01961	O
0.03163	Trip	0.02227	Standard (BSL)
0.03473	Expt.	0.02344	J
0.03571	H	0.02348	Combined (SST-GY)
0.03739	Combined (SST-GY)	0.02576	Combined (BSL)
0.03856	Combined (BSL)	0.02721	H
0.03980	L	0.03883	L
0.03995	J	0.04002	I

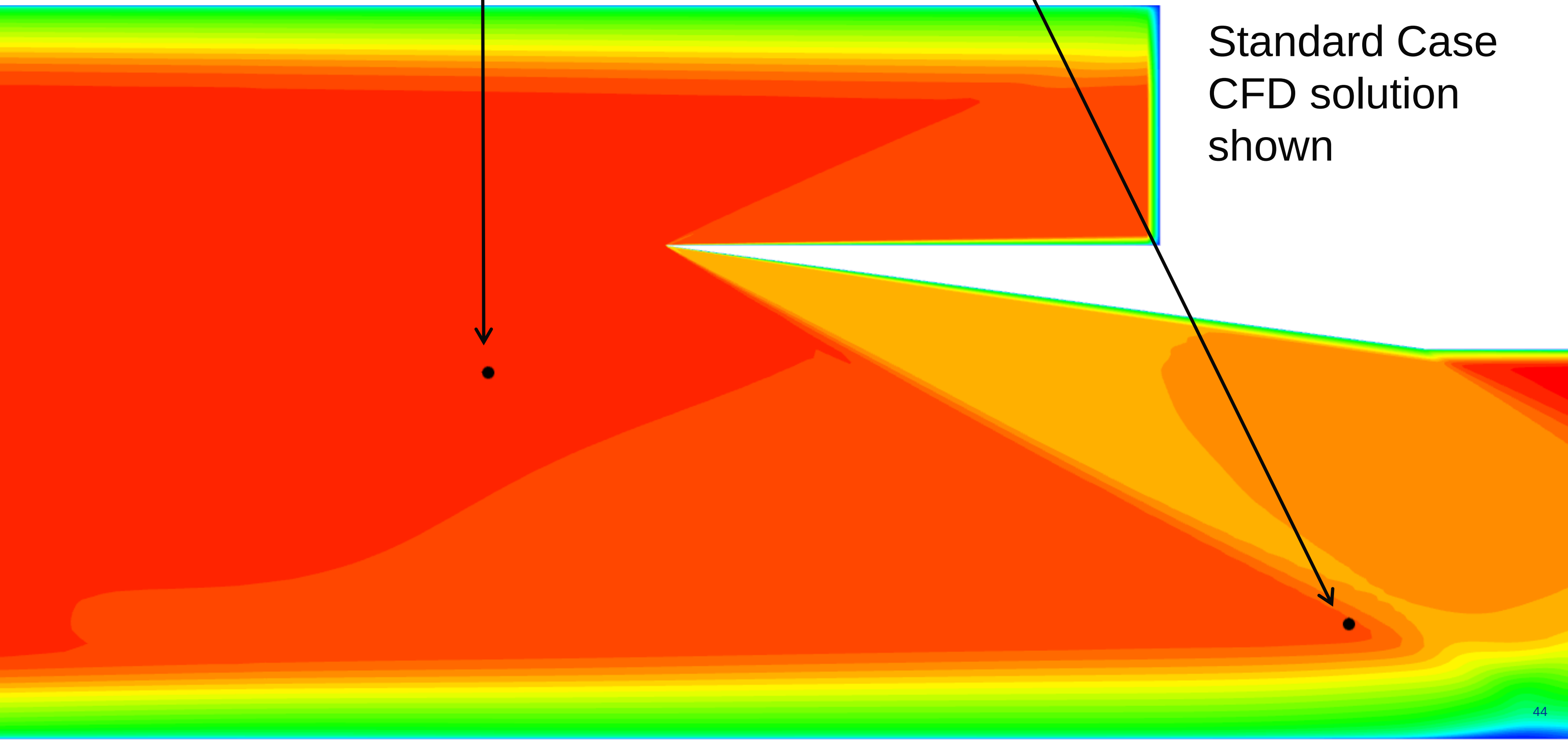
Note all prior workshop CFD analyses utilized a total temperature of 293 K while the new CFD analyses utilized a total temperature of 295.7 K.

Point Comparison Location

A: Taken at center-height, center-span

B: Point of most upstream U_{max} within experimental data plane

Standard Case CFD solution shown

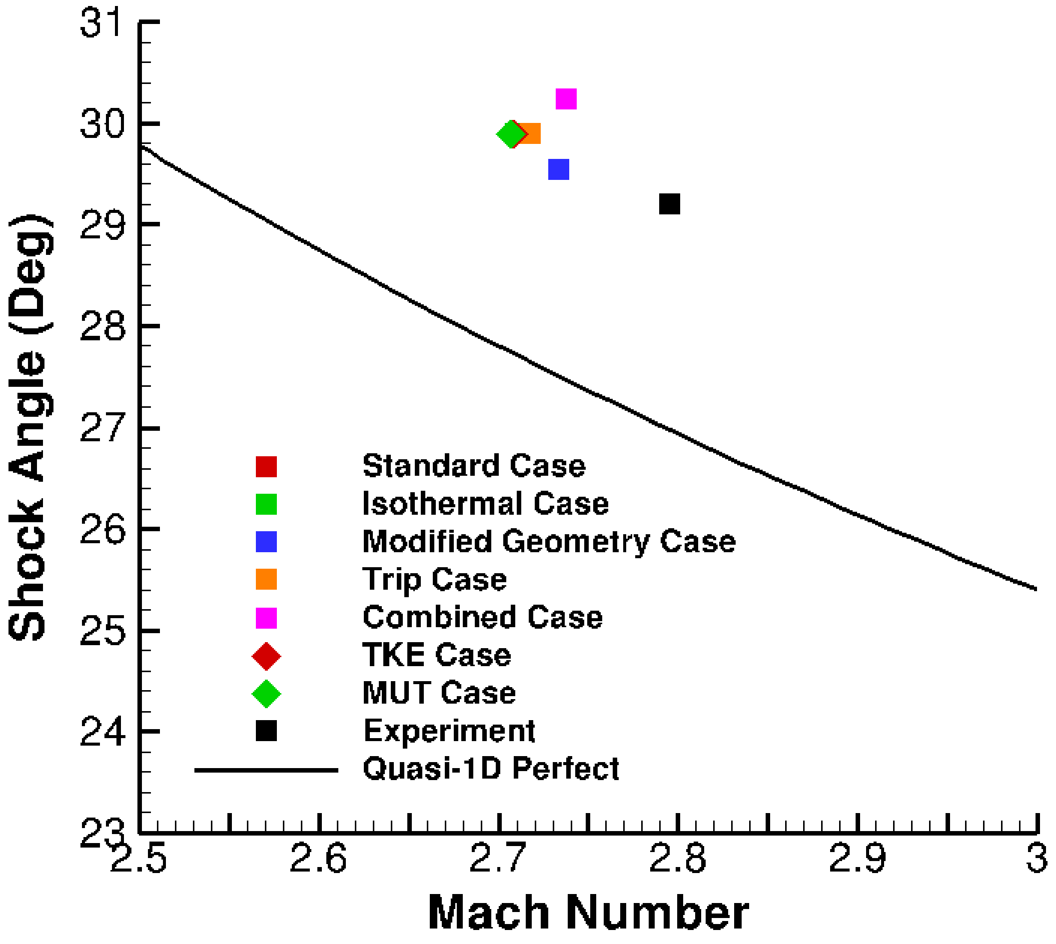


U Velocity Deltas

	Point A		Point B	
Case	**U (m/s)**	**ΔU (m/s)**	**U (m/s)**	**ΔU (m/s)**
Standard	594.600	0.000	587.042	0.000
Isothermal	594.454	-0.146	586.377	-0.665
Modified Geometry	596.567	1.967	586.413	-0.629
Trip	595.186	0.586	587.737	0.695
Combined	596.980	2.380	587.038	-0.004
Experiment	-	-	599.330	12.288

Δ=Case-Standard

Shock Angle



Shock Angle (Deg)
31
30
29
28
27
26
25
24
23
2.5
2.6
2.7
2.8
2.9
3
Mach Number
Standard Case
Isothermal Case
Modified Geometry Case
Trip Case
Combined Case
TKE Case
MUT Case
Experiment
Quasi-1D Perfect

Conclusions

- CFD analyses were performed and generally under predicted the freestream velocities but with improvements.
  - Improved modeling.
  - The flow was shown to be most likely transitional downstream of the throat.
  - SST likely has corner separation too large, which was reduced with SST-GY and BSL.

Conclusions

- A fraction of the measured PIV lag was used with a simple model to modify the CFD solutions.
  - Showed improved comparisons to the experimental data.
  - Future comparisons should have the CFD results augmented in a post-processing step to calculate particle velocities.
- New complimentary metrics:
  - max *u* velocity
  - shock angle

Future Work

- Sensitivities to address:
  – Additional geometric parameters
  – Turbulence model and parameters
  – Heat transfer boundary conditions
    - Conjugate heat transfer
  – Boundary-layer transition/trip location and model

Future Work

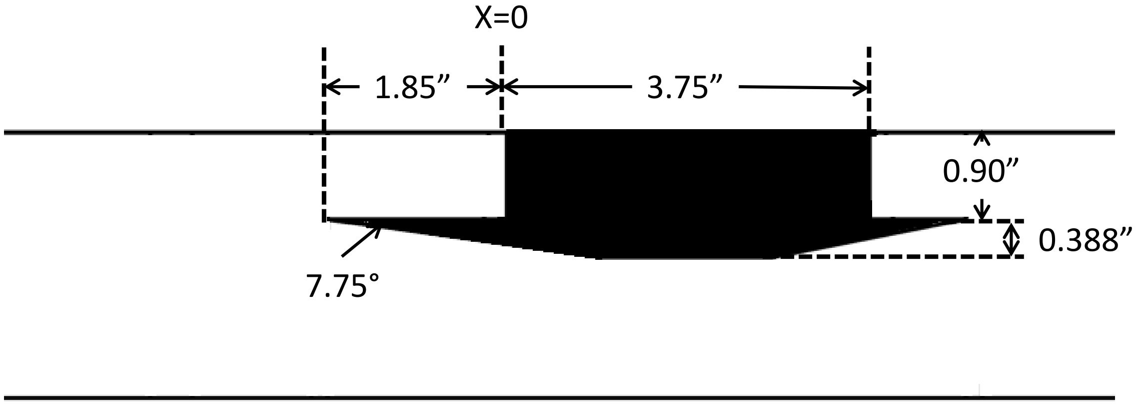
- The simplified PIV model should be improved on.
  - Calculating the particle lag based on the forces exerted on the individual particles by the air (including particle size distribution).
  - Obtaining flow field snapshots at two instances in time.
    - Snapshots would then be processed using the same PIV post-processing algorithm used with the experimental data.

Acknowledgements

- Air Force Research Laboratory, Air Vehicle Directorate, AFRL/RB and the interaction with the U.S. Air Force Collaborative Center for Aeronautical Sciences
- NASA Fundamental Aeronautics Program High Speed Project and the NASA High End Computing Program (HECC)
- Marshall Galbraith

Backup Slides

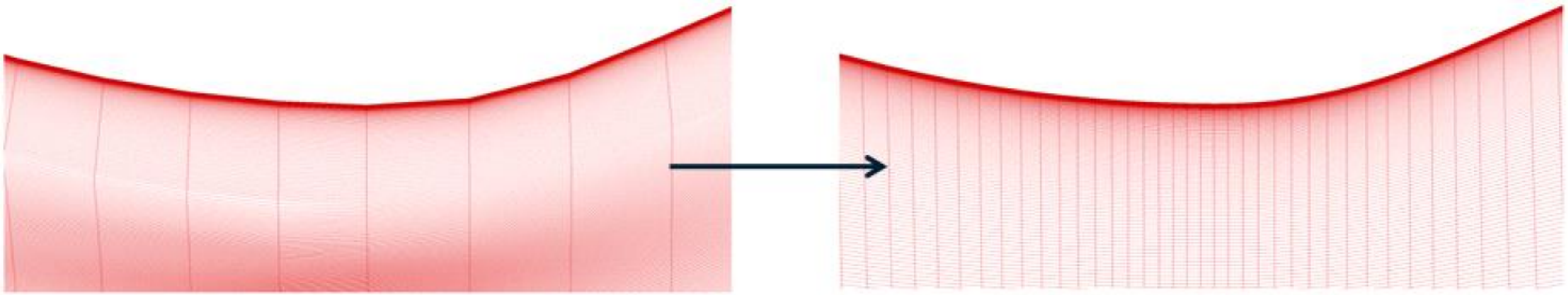
Geometry



	Throat (in)	Test Section (in)	A/A*
As Designed	2.25 x 0.742	2.25 x 2.75	3.7062
As Installed	2.25 x 0.725	2.25 x 2.72	3.7847

Error of “As Installed” Measurement: +/- 0.005 in

Throat Modification



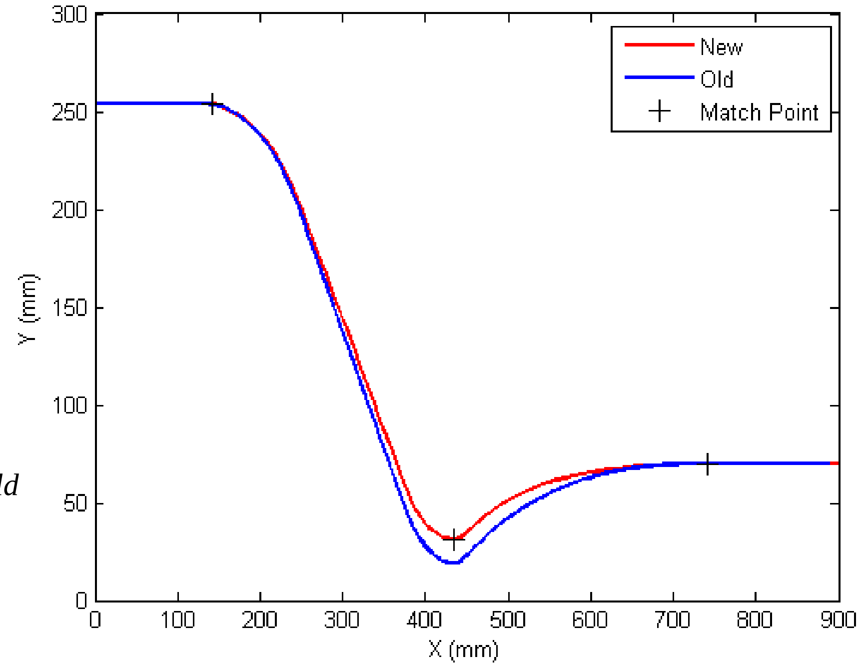
Added an additional 50 grid points to base grid to define the nozzle contour

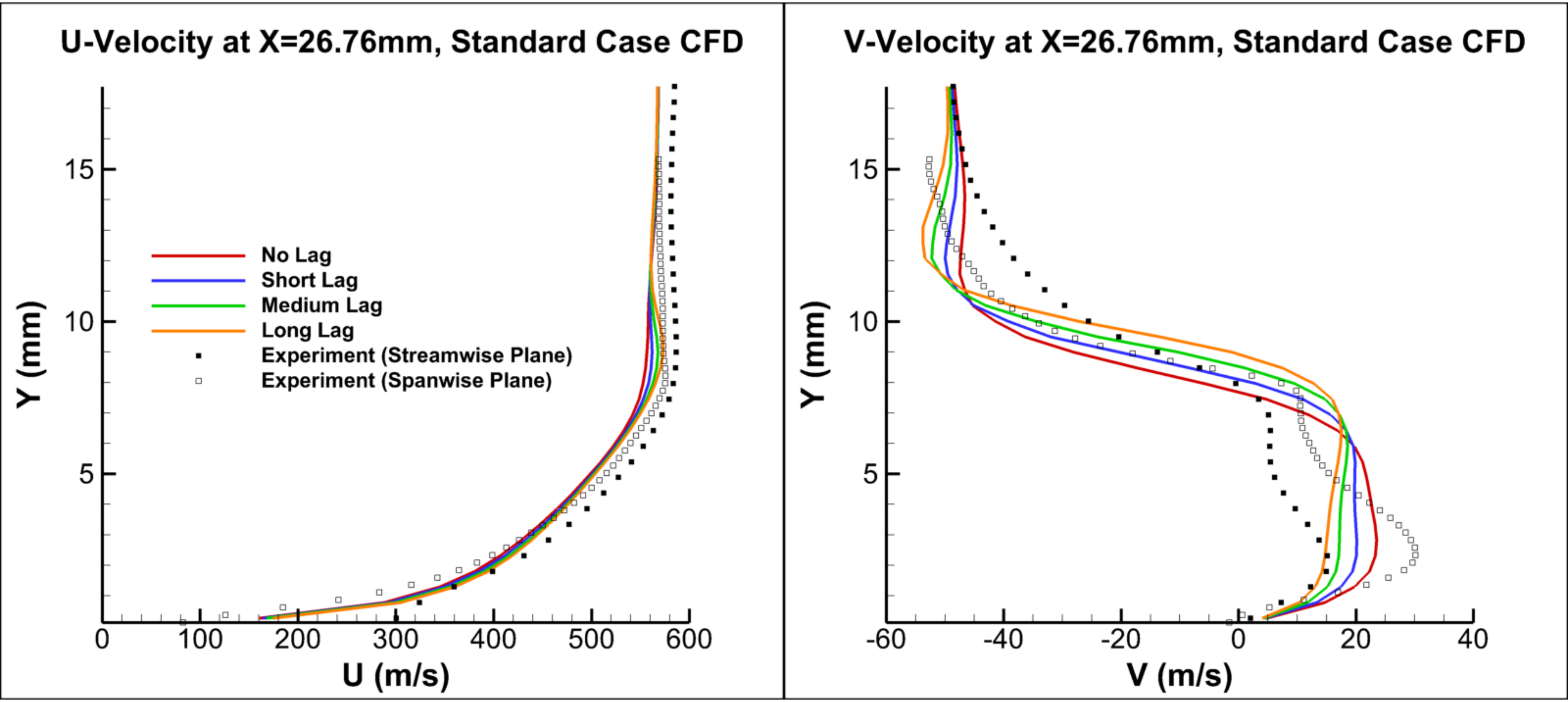
Grid Modification

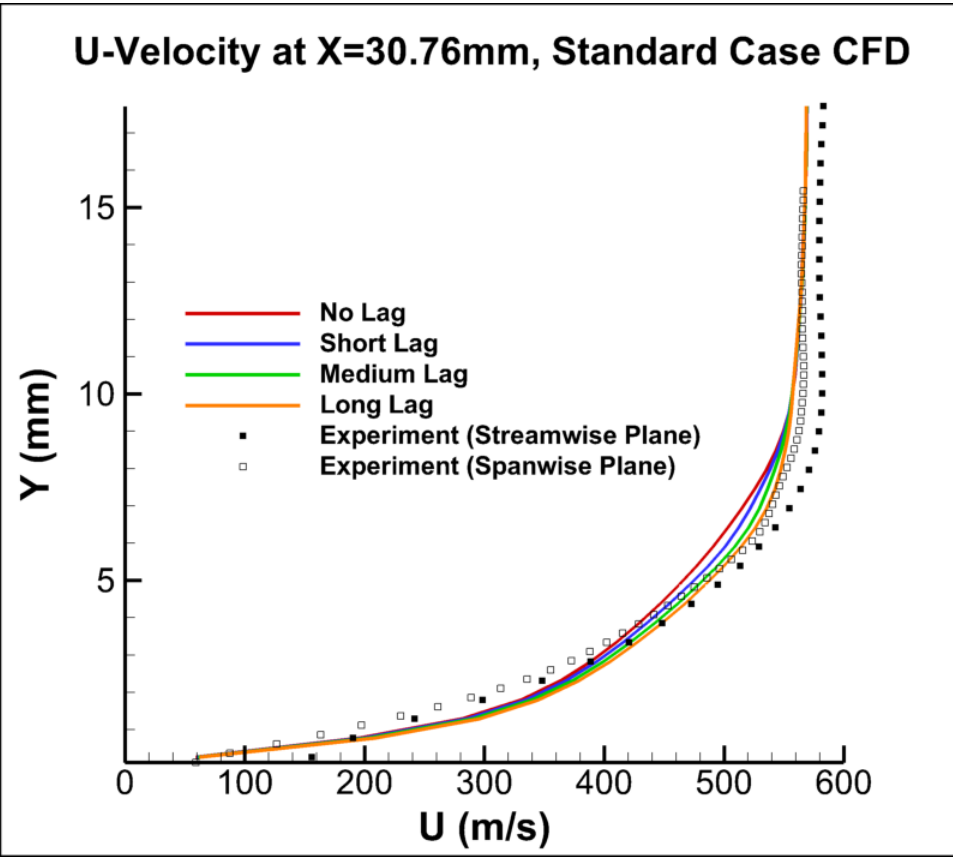
- Raised bottom wall.
- Modified nozzle contour.

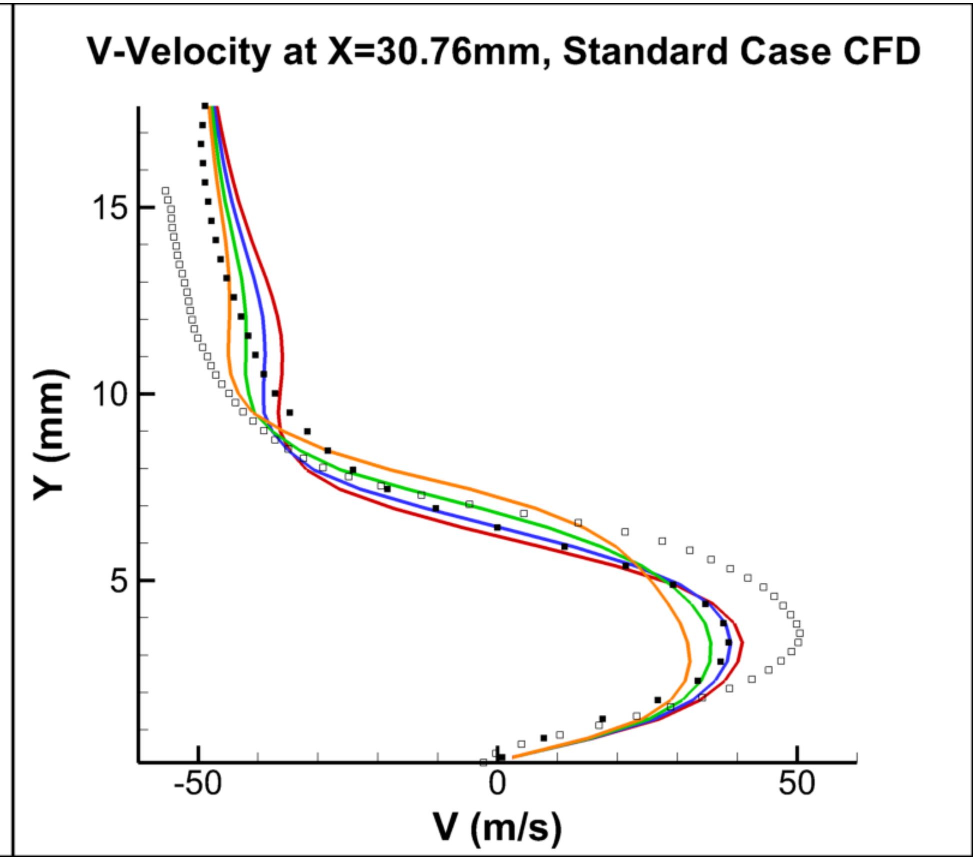
$$y_{new} = \left(y_{throat,new} - y_{throat,old}\right)\left(\frac{x_1 - x}{x_1 - x_{throat}}\right)^m + y_{old}$$

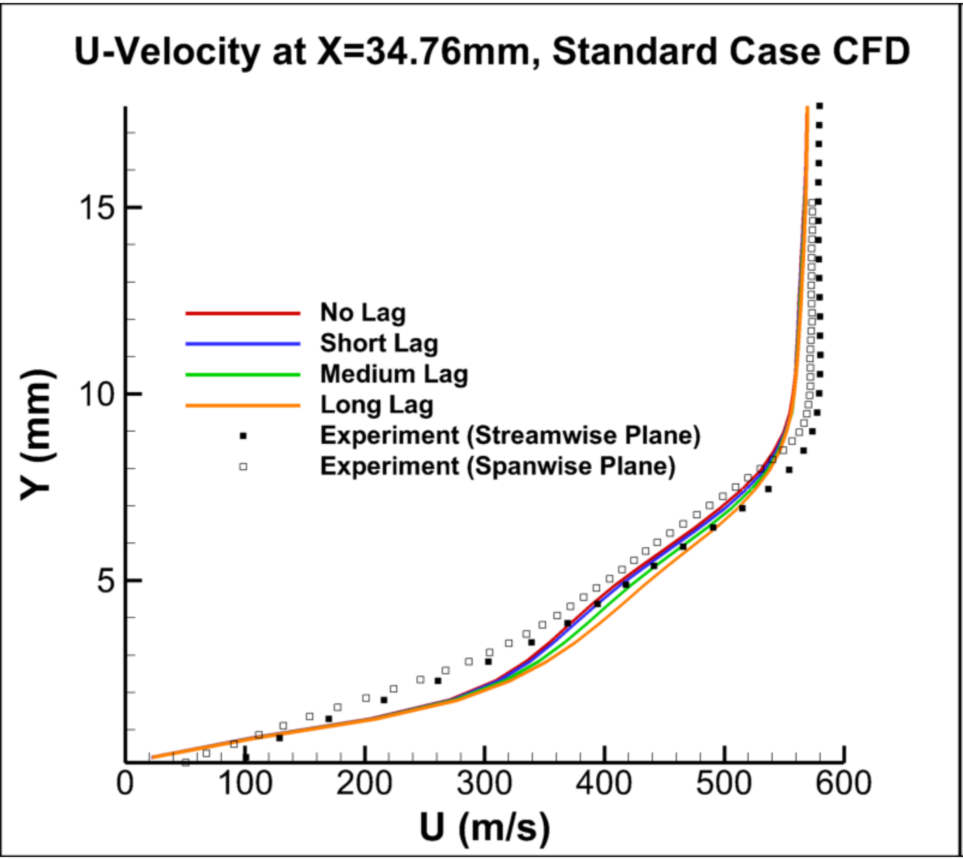
$$m = 0.5 + 1.5\left(\frac{x_{throat} - x}{x_{throat} - x_1}\right)$$

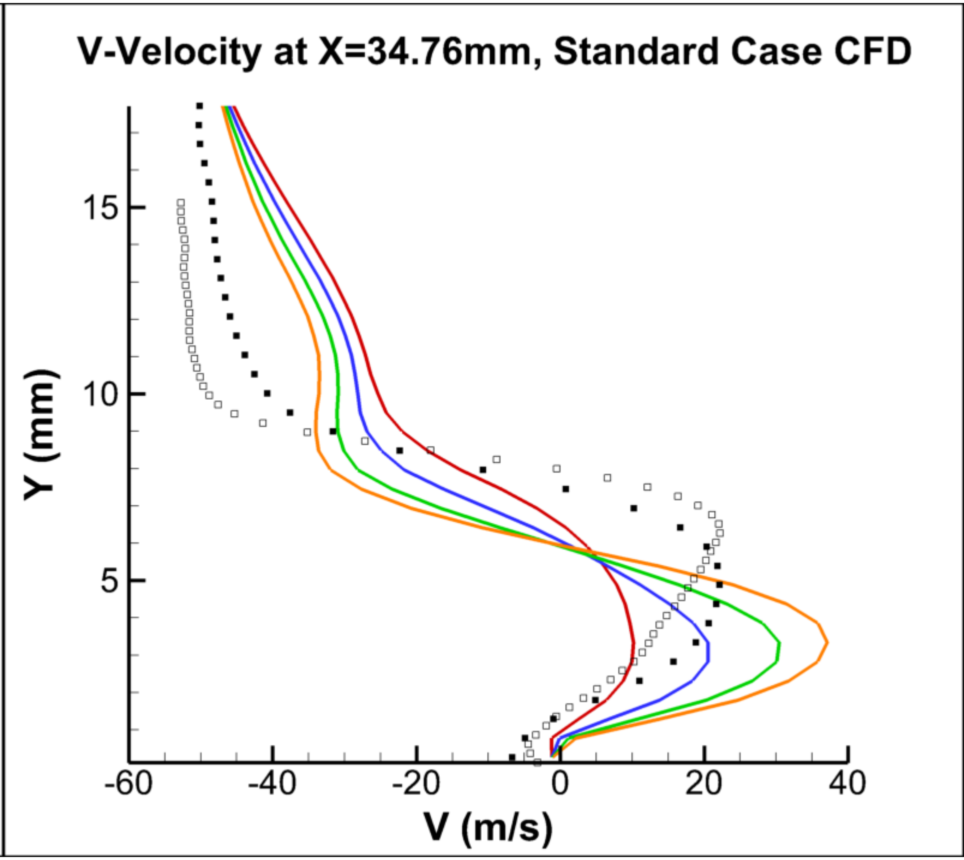


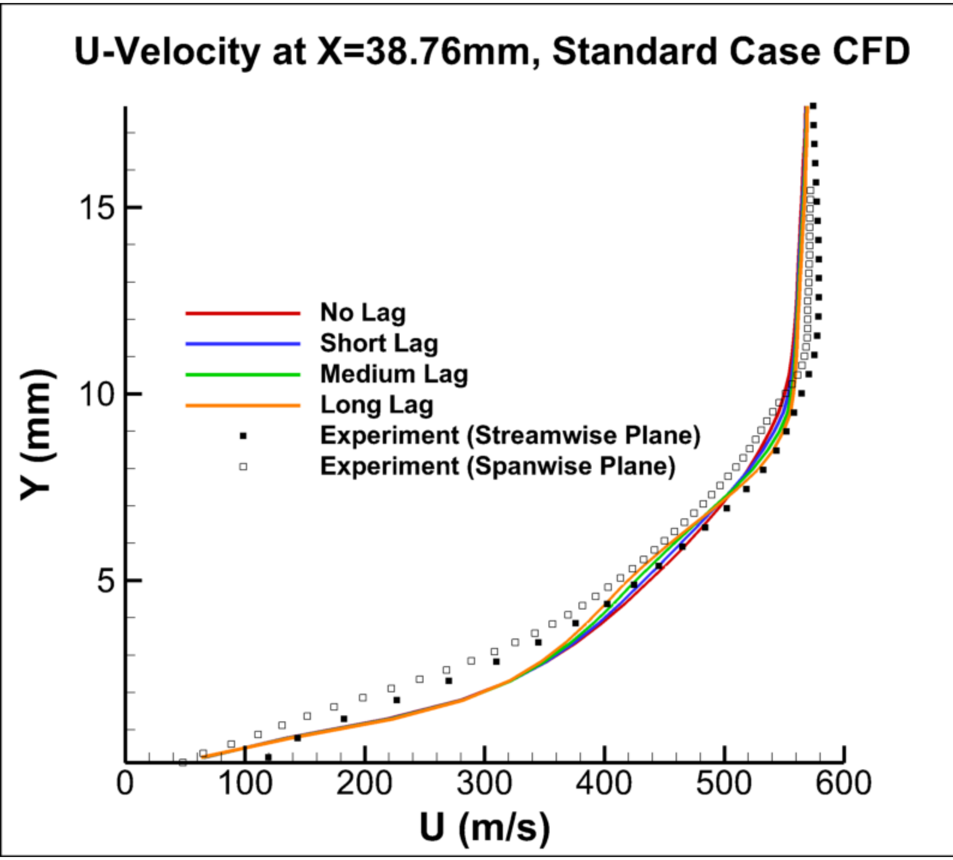

U-Velocity at X=26.76mm, Standard Case CFD
Y (mm)
U (m/s)
0
100
200
300
400
500
600
5
10
15
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
V-Velocity at X=26.76mm, Standard Case CFD
Y (mm)
V (m/s)
-60
-40
-20
0
20
40

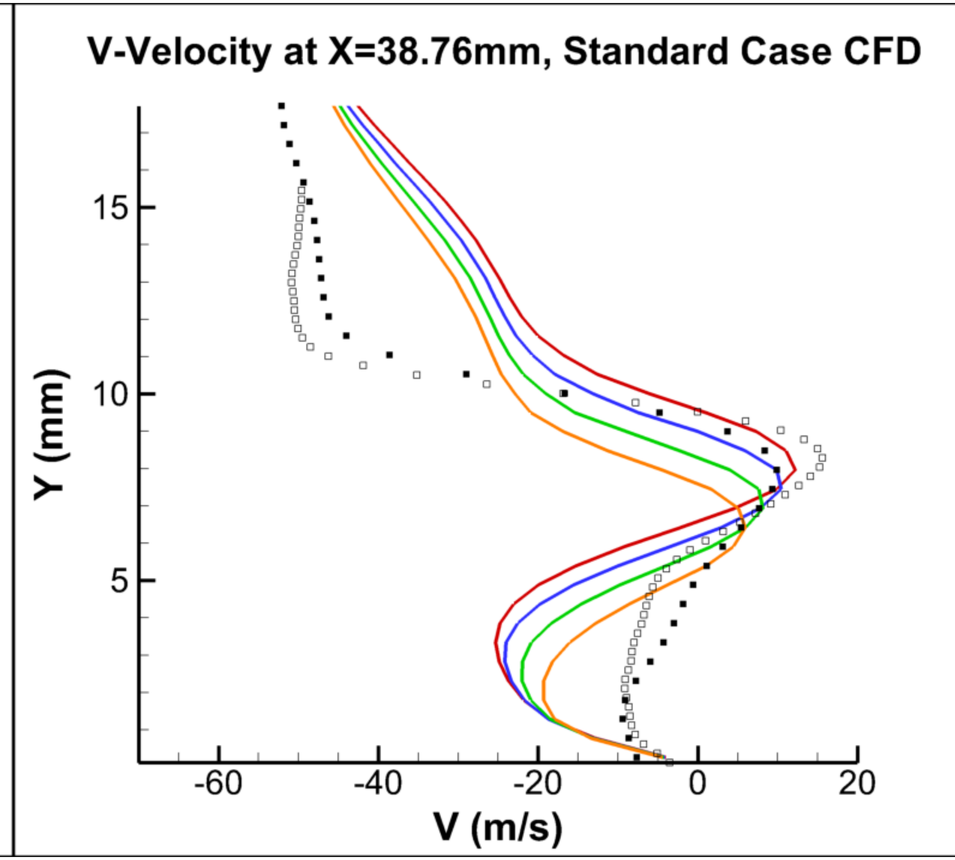

U-Velocity at X=30.76mm, Standard Case CFD
Y (mm)
15
10
5
0
100
200
300
400
500
600
U (m/s)
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)

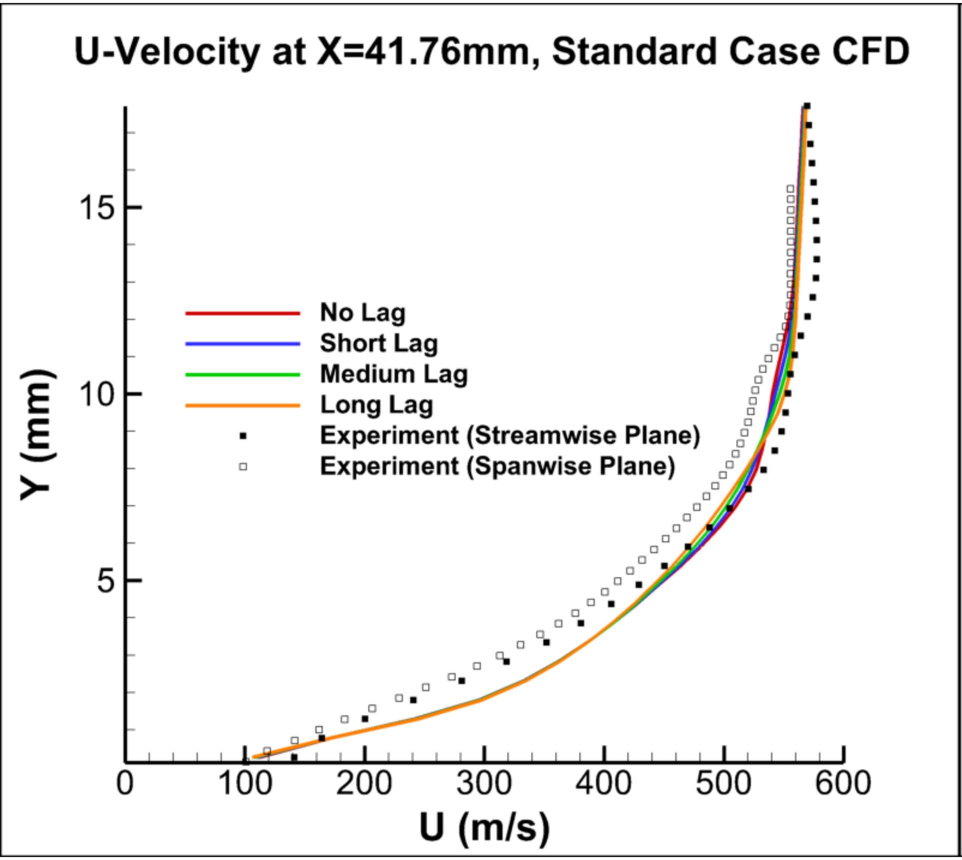

V-Velocity at X=30.76mm, Standard Case CFD
Y (mm)
15
10
5
-50
0
50
V (m/s)

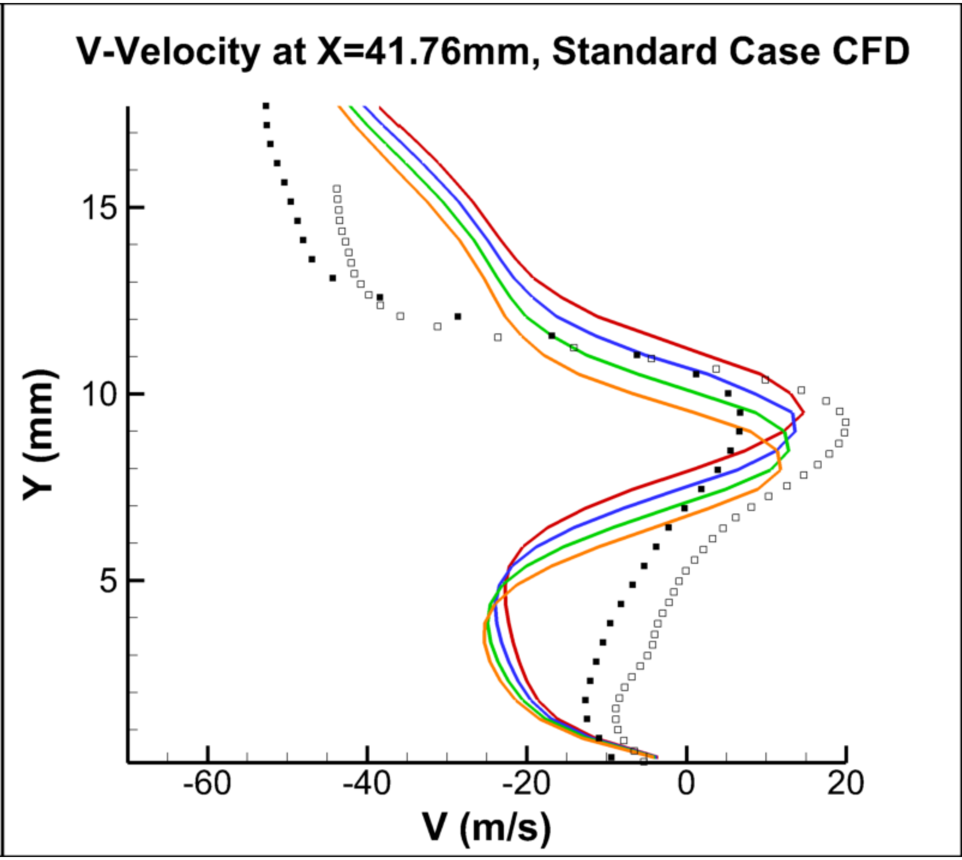

U-Velocity at X=34.76mm, Standard Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
15
10
5
0
100
200
300
400
500
600
U (m/s)

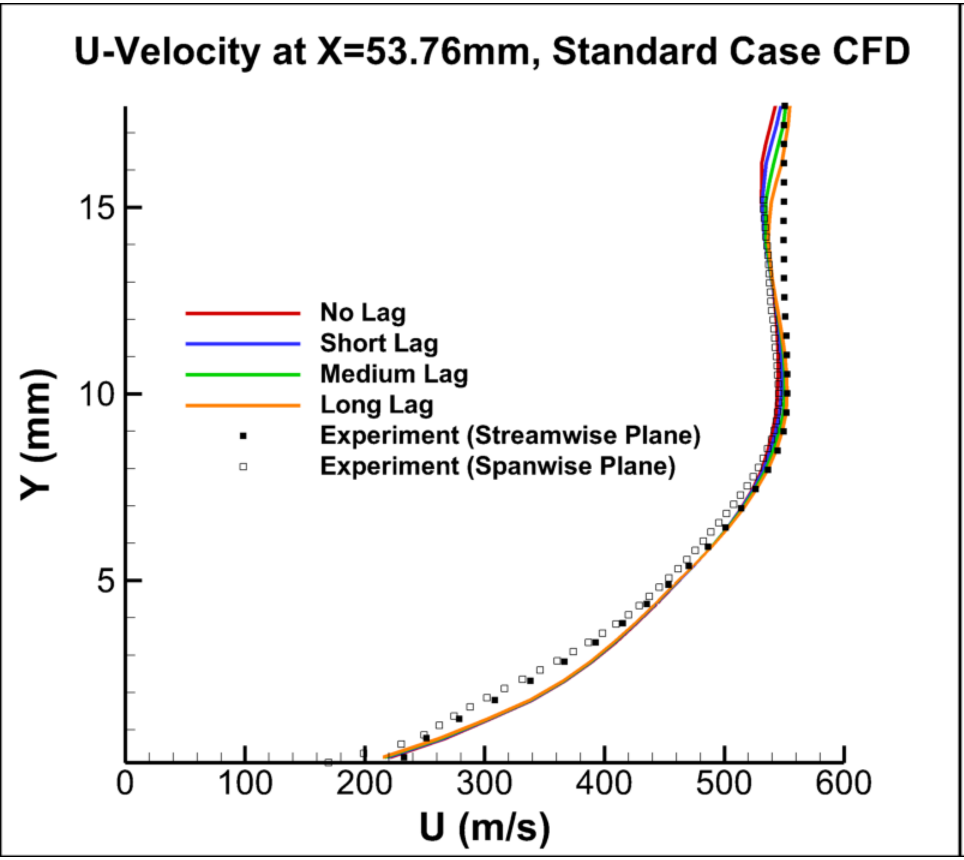

V-Velocity at X=34.76mm, Standard Case CFD
Y (mm)
15
10
5
-60
-40
-20
0
20
40
V (m/s)

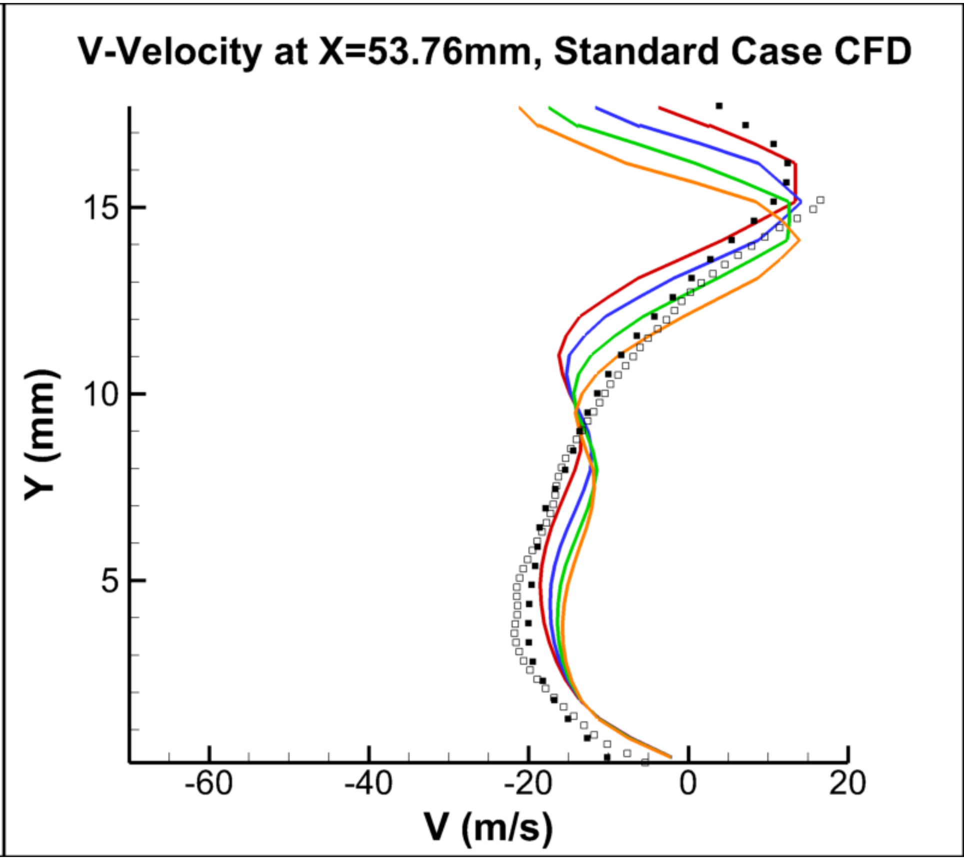

U-Velocity at X=38.76mm, Standard Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
U (m/s)
0
100
200
300
400
500
600
5
10
15

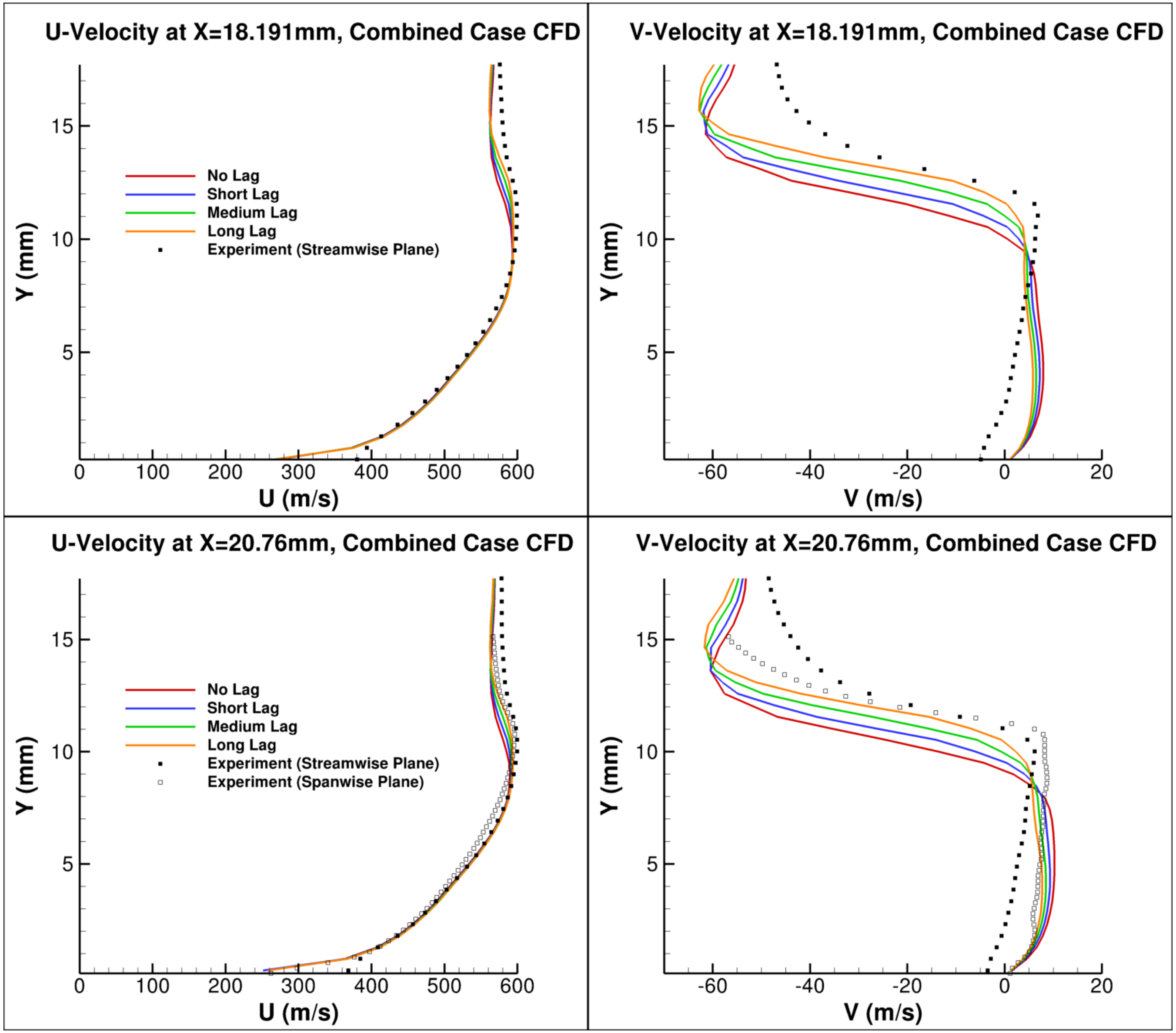

V-Velocity at X=38.76mm, Standard Case CFD
Y (mm)
V (m/s)
-60
-40
-20
0
20
5
10
15

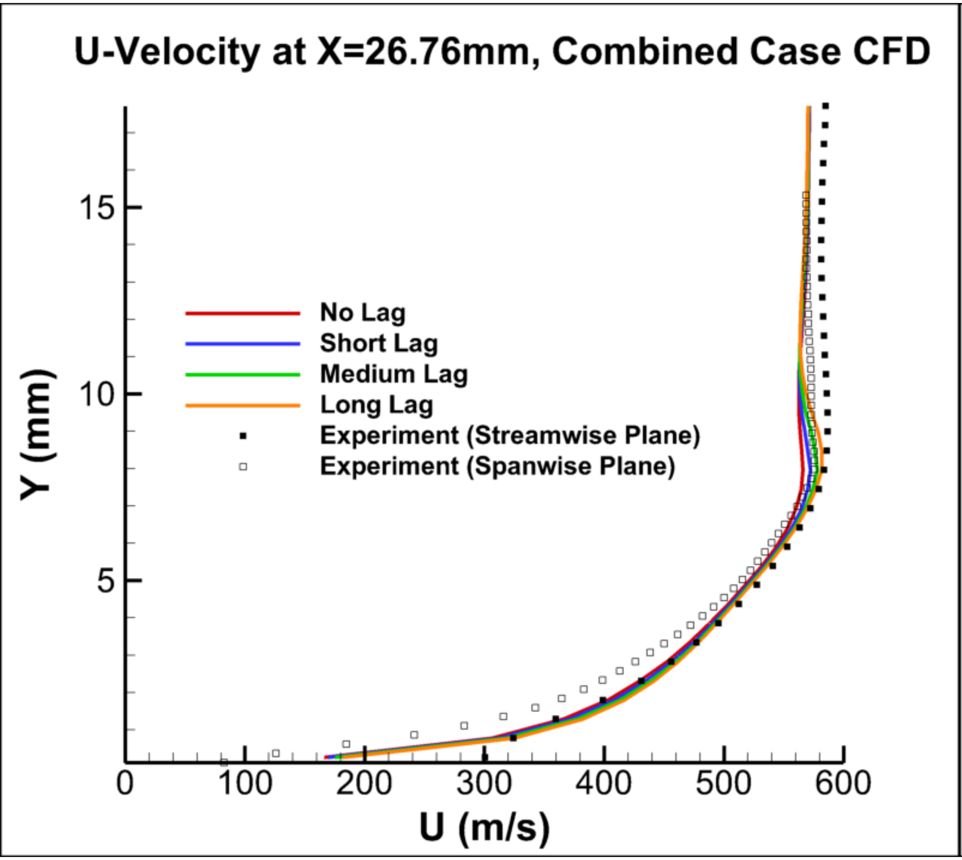

U-Velocity at X=41.76mm, Standard Case CFD
Y (mm)
U (m/s)
0
100
200
300
400
500
600
5
10
15
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)

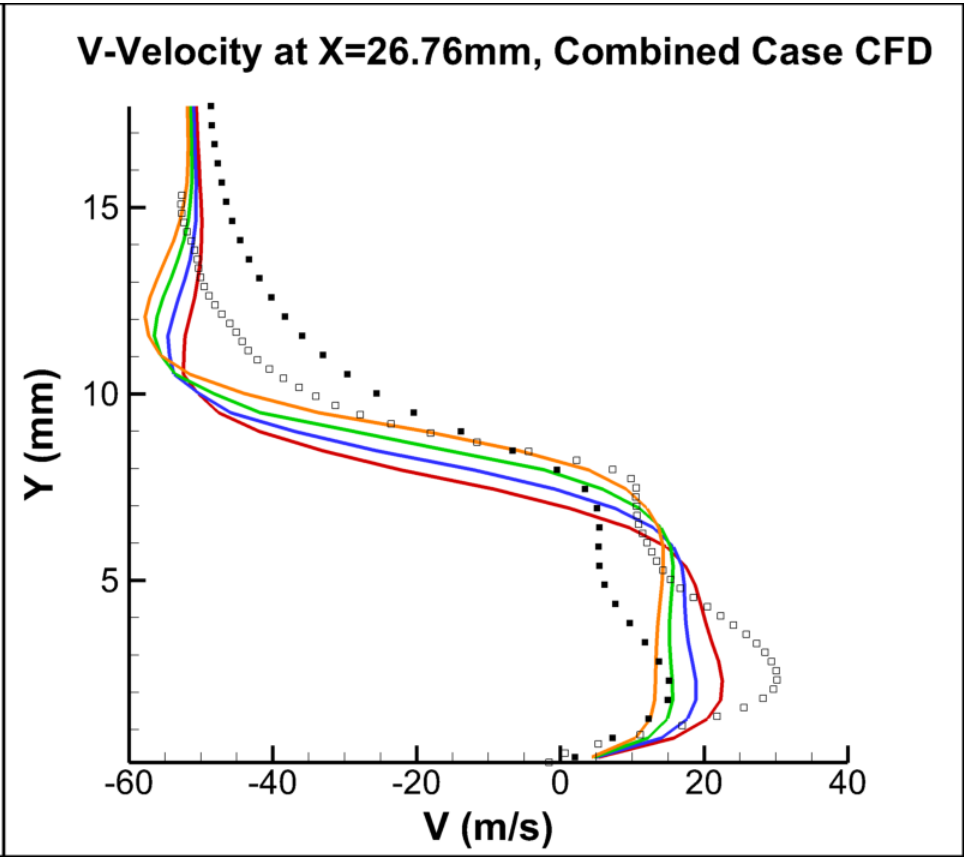

V-Velocity at X=41.76mm, Standard Case CFD
Y (mm)
V (m/s)
-60
-40
-20
0
20
5
10
15

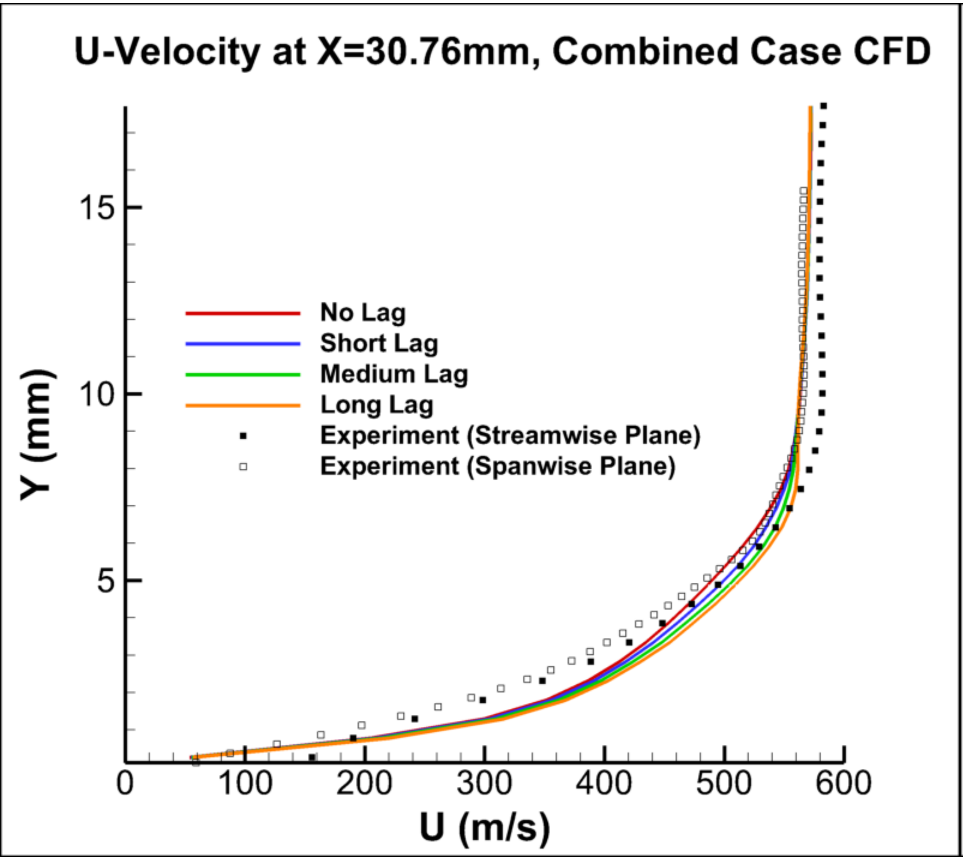

U-Velocity at X=53.76mm, Standard Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
5
10
15
0
100
200
300
400
500
600
U (m/s)

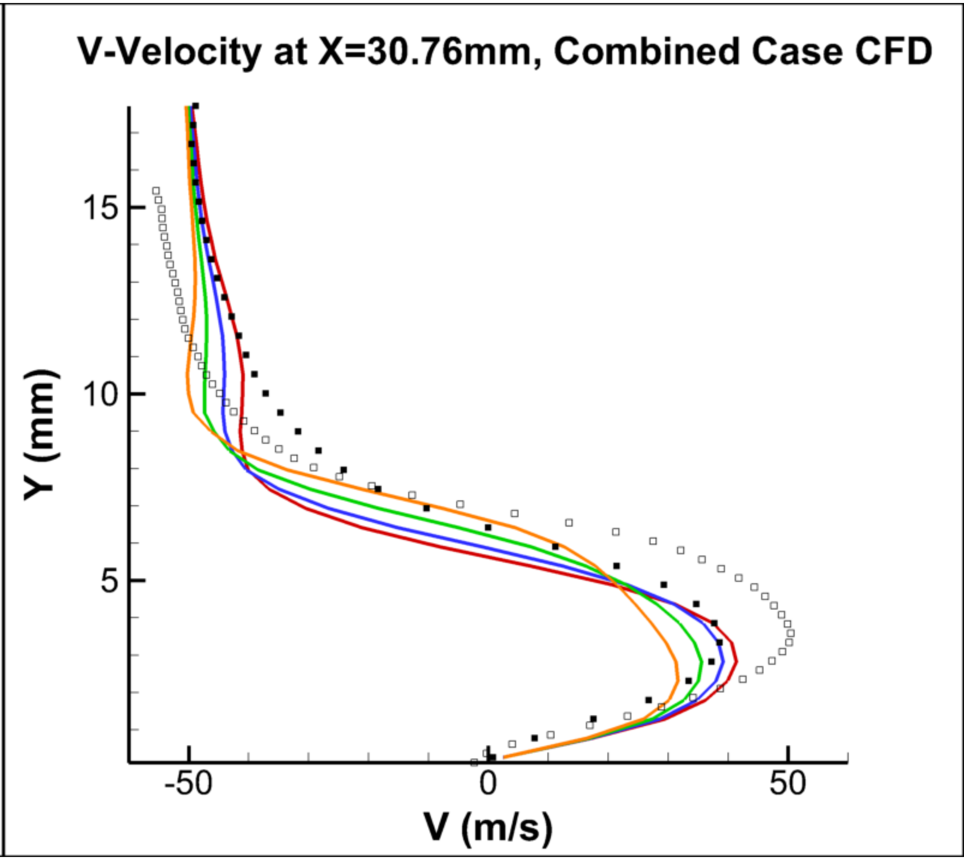

V-Velocity at X=53.76mm, Standard Case CFD
Y (mm)
5
10
15
-60
-40
-20
0
20
V (m/s)

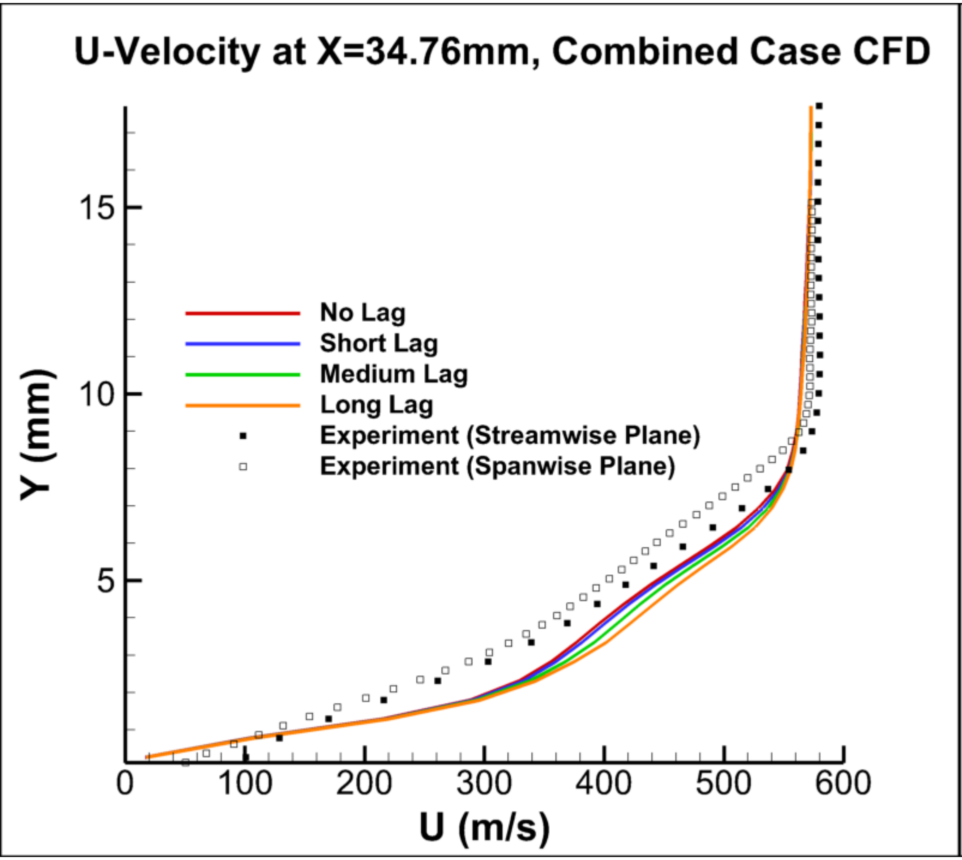

U-Velocity at X=18.191mm, Combined Case CFD
V-Velocity at X=18.191mm, Combined Case CFD
U-Velocity at X=20.76mm, Combined Case CFD
V-Velocity at X=20.76mm, Combined Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
U (m/s)
V (m/s)
0
100
200
300
400
500
600
-60
-40
-20
20
5
10
15

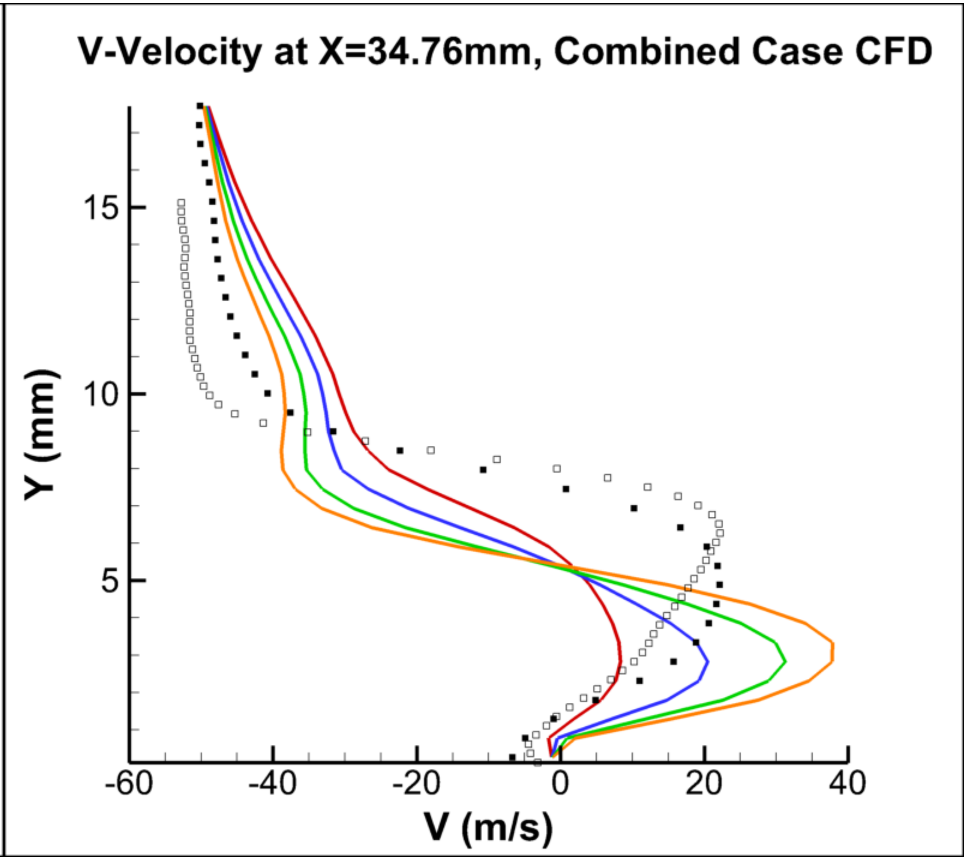

U-Velocity at X=26.76mm, Combined Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
15
10
5
0
100
200
300
400
500
600
U (m/s)

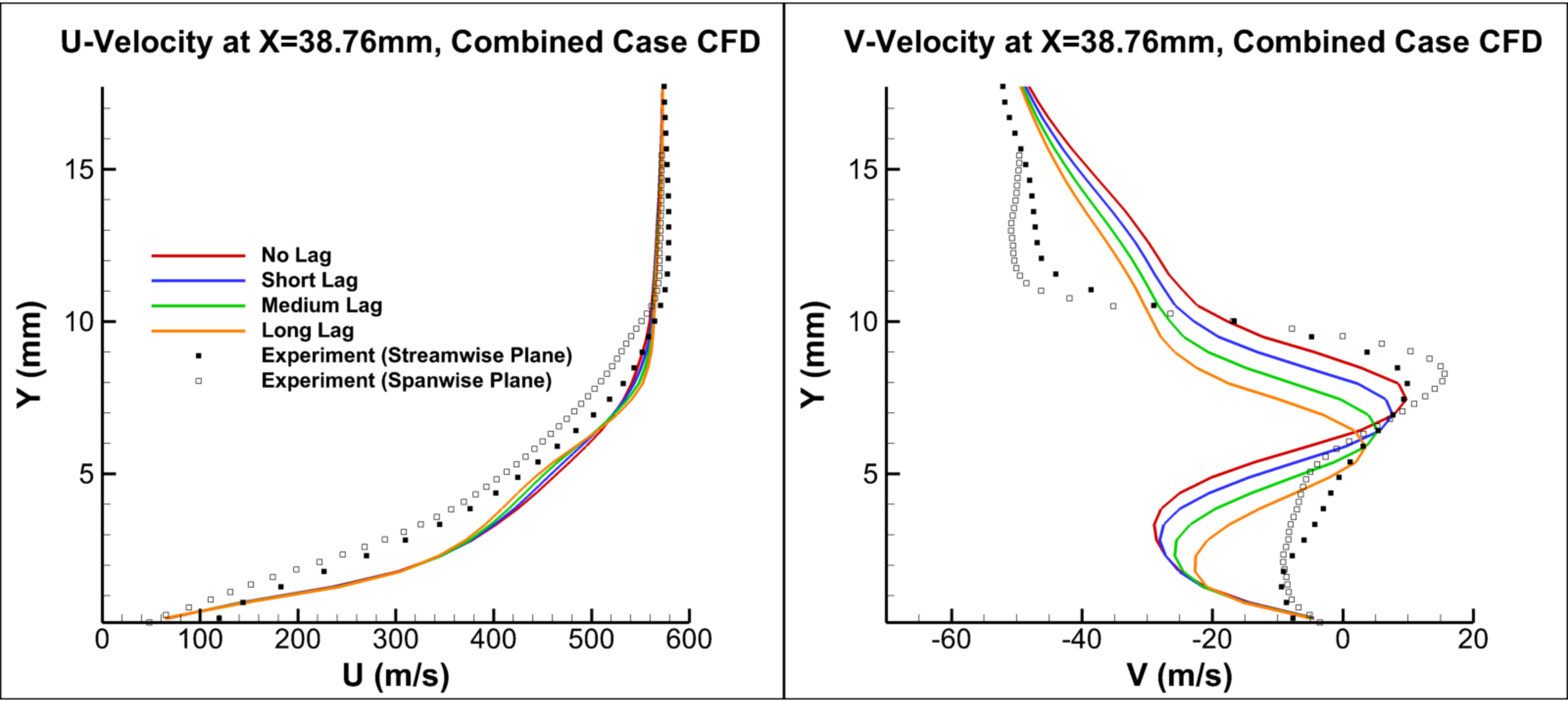

V-Velocity at X=26.76mm, Combined Case CFD
Y (mm)
15
10
5
-60
-40
-20
0
20
40
V (m/s)


U-Velocity at X=30.76mm, Combined Case CFD
Y (mm)
U (m/s)
0
100
200
300
400
500
600
5
10
15
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)

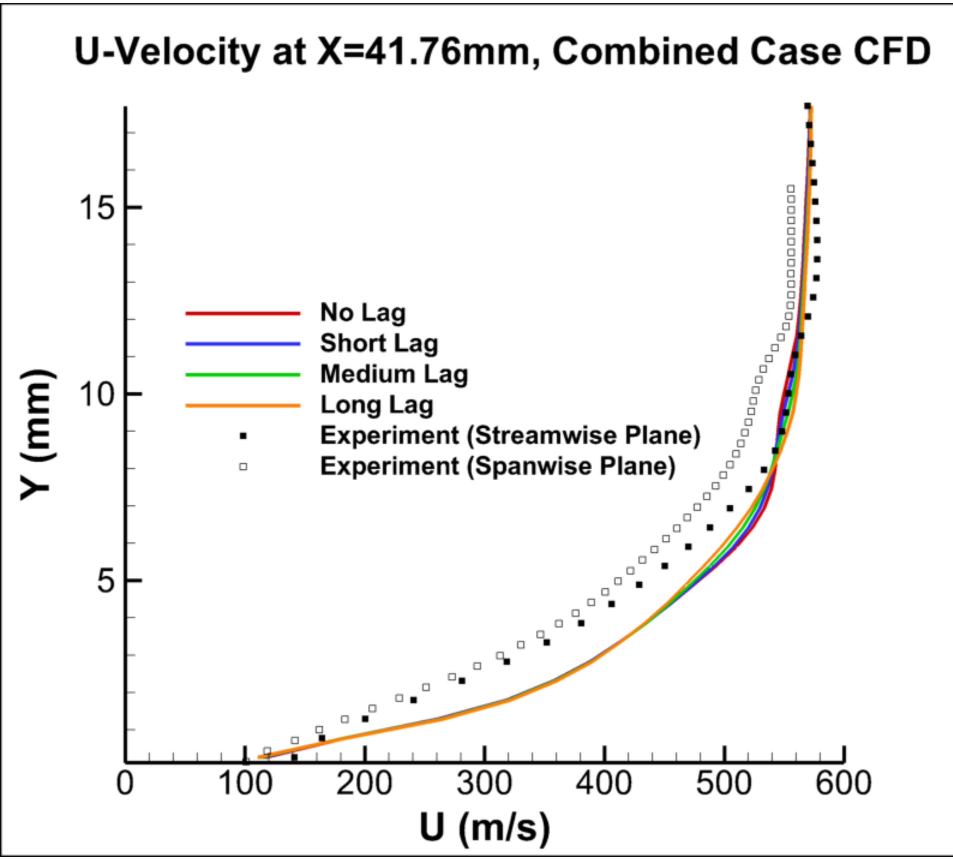

V-Velocity at X=30.76mm, Combined Case CFD
Y (mm)
V (m/s)
-50
0
50
5
10
15

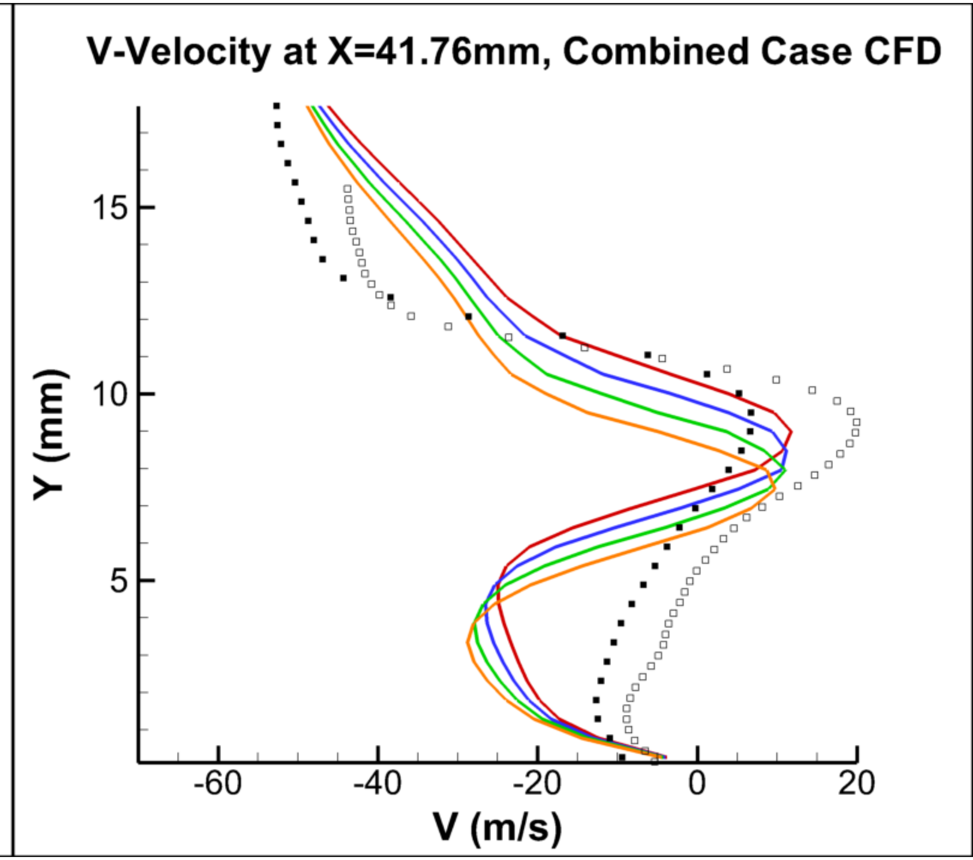

U-Velocity at X=34.76mm, Combined Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
U (m/s)
0
100
200
300
400
500
600
5
10
15

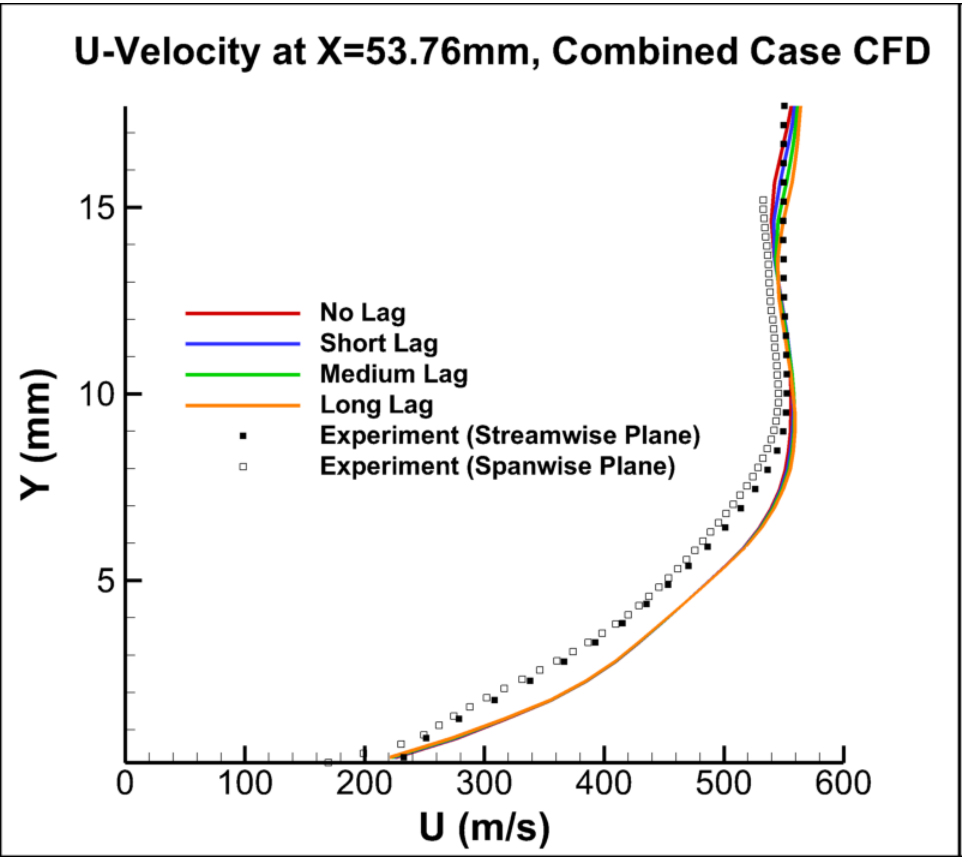

V-Velocity at X=34.76mm, Combined Case CFD
Y (mm)
V (m/s)
-60
-40
-20
0
20
40
5
10
15

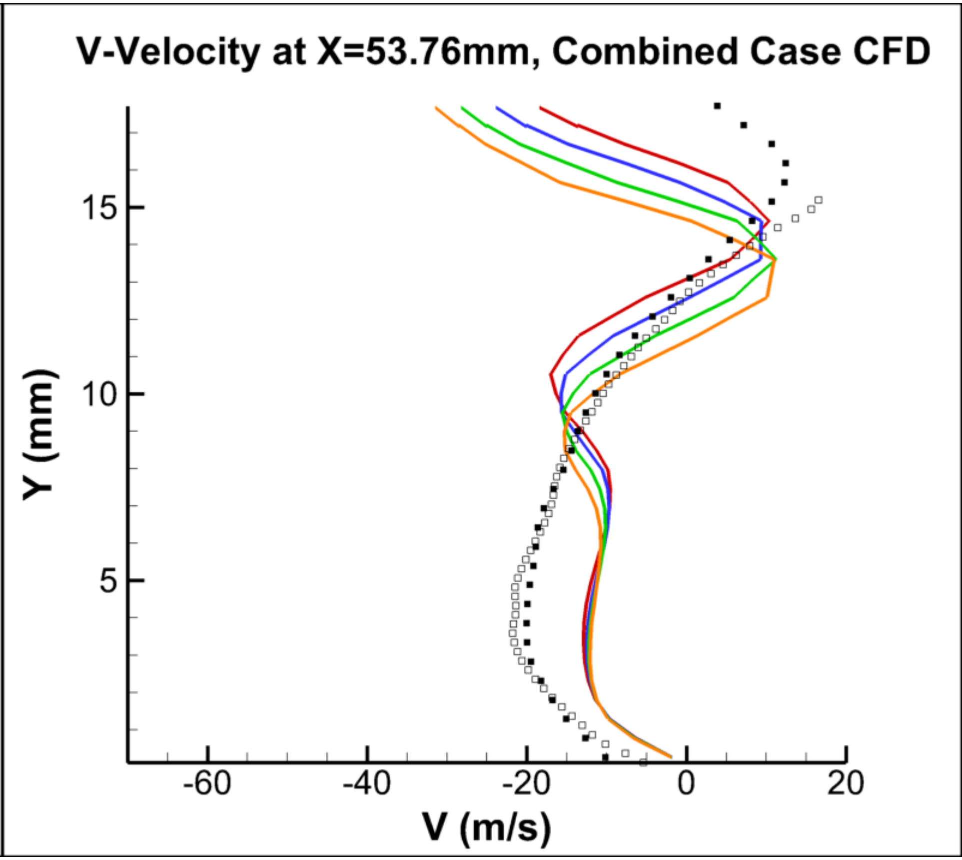


U-Velocity at X=38.76mm, Combined Case CFD
Y (mm)
U (m/s)
0
100
200
300
400
500
600
5
10
15
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
V-Velocity at X=38.76mm, Combined Case CFD
Y (mm)
V (m/s)
-60
-40
-20
0
20


U-Velocity at X=41.76mm, Combined Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
U (m/s)
0
100
200
300
400
500
600
5
10
15


V-Velocity at X=41.76mm, Combined Case CFD
Y (mm)
V (m/s)
-60
-40
-20
0
20
5
10
15


U-Velocity at X=53.76mm, Combined Case CFD
No Lag
Short Lag
Medium Lag
Long Lag
Experiment (Streamwise Plane)
Experiment (Spanwise Plane)
Y (mm)
15
10
5
0
100
200
300
400
500
600
U (m/s)


V-Velocity at X=53.76mm, Combined Case CFD
Y (mm)
15
10
5
-60
-40
-20
0
20
V (m/s)

1. Throat
2. Trip Location
3. Start of Straight Section
4. Wedge Leading Edge
5. Wedge Trailing Edge